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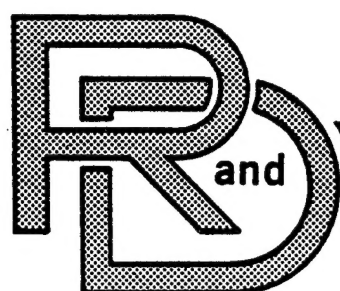# R and D CENTER LABORATORY

TECHNICAL REPORT

NO. 12790

INVESTIGATION OF ADVANCED

SUSPENSION TECHNOLOGY CONCEPTS

FOR MILITARY TRACKED VEHICLES

OCTOBER 1983

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Several suspension concepts are investigated for the purpose of improving the ride quality of military tracked vehicles. Areas of advanced technology required for these suspension concepts are also investigated. These include terrain elevation sensing, digital signal processing, on-board microprocessors, suspension components with rapidly variable characteristics, and appropriate control logic.
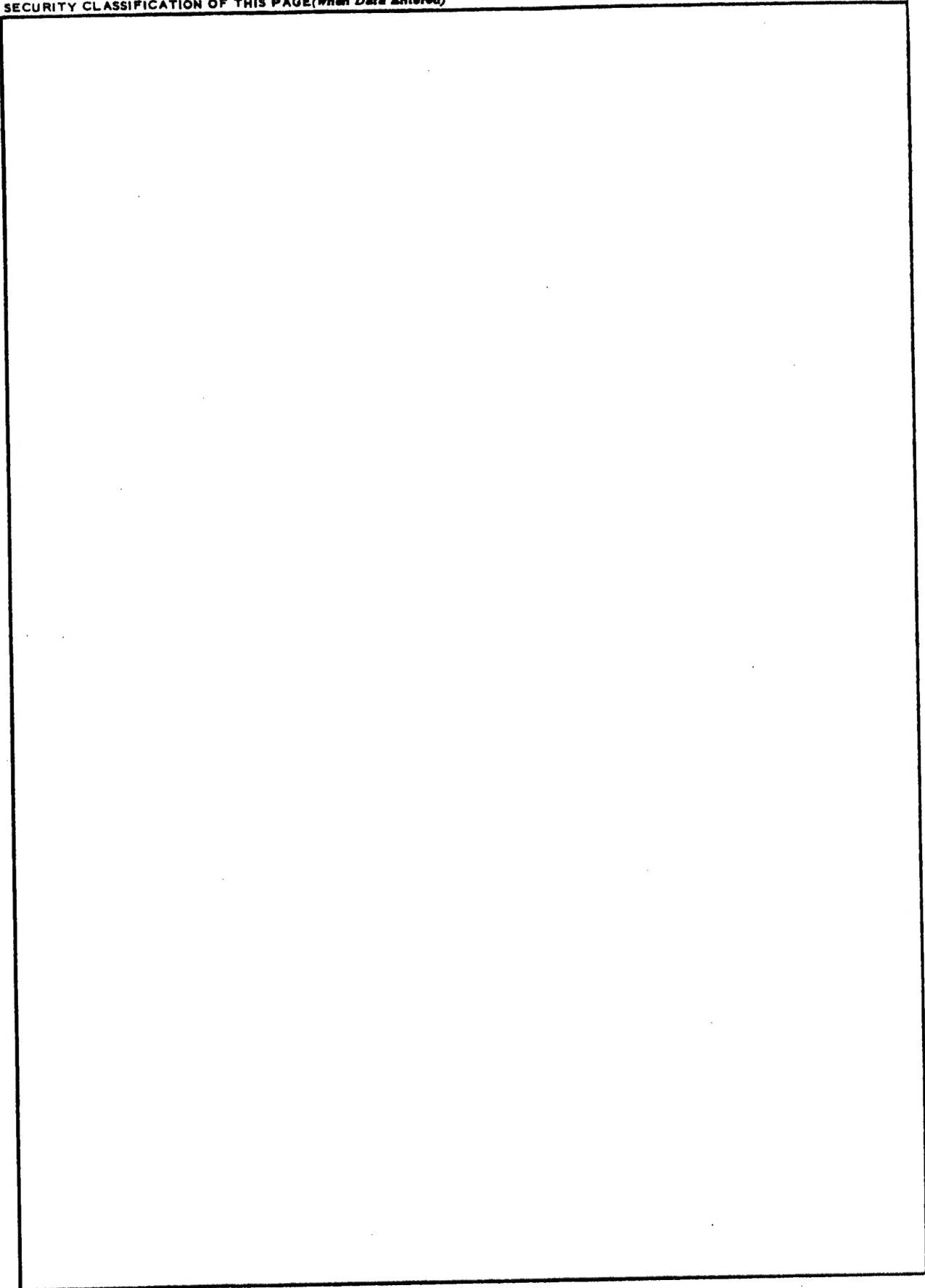
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PREFACE

This work was performed for DRSTA-RCKT during the period January 1980 - December 1980 under the direction of Mr. Michael Kaifish. Besides describing in detail work performed solely by the author, this document also summarizes work performed by Mr. Frank Hoogterp of TACOM, Dr. K. C. Cheok and Dr. N. K. Loh of Oakland University and the Lord Corporation.

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1.0. INTRODUCTION

Since 1980, the Applied Research Function has been investigating advanced suspension system concepts for the Track and Suspension Sub-Function. These concepts all presume on-the-move adjustability in the springing and/or the damping characteristics of the suspension system. In order to design this type of suspension, it was recognized from the beginning that:

o   a system would be required for sensing some of the vehicle states, and perhaps for sensing and interpreting the terrain;

o   that control logic would be needed for determining the optimum suspension adjustments as a function of terrain and vehicle parameters;

o   that an on-board microprocessor would be needed to carry out the required computations and for actuating the controllable suspension elements.

Thus, the overall approach was to identify in the technical literature the current state-of-the-art approaches to optimal suspension design and control strategies; evaluate these strategies for potential application to combat vehicles; develop new strategies or modify existing ones to best suit the program objectives; and simulate selected strategies (either found in the literature or developed by the investigators) in a validated vehicle ride quality computer model.

Section 5.0. of this report documents in historical order the investigations conducted and the improvements in ride quality achieved with advanced suspension systems designs and control strategies.

2.0. OBJECTIVE

The primary objectives of this advanced suspension technology investigation are:

o   to identify and simulate vehicle suspension system control strategies which will extend combat vehicle operational capabilities to higher speeds and rougher terrains by increasing the overall comfort of the crew, the tracking capability of the gunner, and the vibrational environment of the fire control system;

o   to specify and identify potential controllable suspension system components, sensors, and microprocessor hardware required to implement and field test a suspension system control strategy.

3.0. CONCLUSIONS

Terrain elevation sensing on board a moving vehicle could be accomplished by a sonar reflective sensor or a laser used in combination with wheel-mounted accelerometers. (Section 5.1. and Appendix A).

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Digital filtering and other digital signal processing techniques using the 16-bit arithmetic available with current microprocessors can be used to identify the overall roughness and the wavelength composition of a terrain from a series of terrain elevation values. (Section 5.2. and 5.3.).

The optimum damping level for a given vehicle on a particular terrain segment can be well-estimated by a combination of linear regression and the computation of a frequency normalized terrain roughness calculation technique. (Section 5.4.).

Substantial improvement in comfort-limited vehicle speed is attainable with a relatively simple scheme which adjusts damping level as a function of time-averaged vehicle pitch rate. (Section 5.5.).

Dramatic improvements in vehicle speed and the elimination of resonant response can be obtained by using passive on-off dampers with the appropriate control logic. (Section 5.6.).

4.0. RECOMMENDATIONS

Extension of the investigation on advanced suspension technology concept may include the following:

Further investigation on the digital filtering techniques proposed in this report for determining optimum adaptive damping levels for vehicle suspension system. The developed suspension control law may be tested using a laboratory adaptive suspension concept model or through simulations.

Development of adaptive suspension control law using direct parameter optimization technique. The optimization objective may consist directly of minimizing the average power absorbed at a given location on a vehicle. The resulting control algorithm may involve on-off (bang-bang) control logic and continuous control logic.

Development of adaptive suspension control logic based on overall vehicle suspension performance. A model reference adaptive control suspension scheme may be suggested.

Development of optimal suspension control system using optimal and preview control techniques. The techniques consist of sensing or predicting future inputs (e.g., the terrain being approached) and employing the information to control and improve the vehicle ride.

Extensive digital computer simulation for verifying potential ride improvement that can be achieved in military vehicles using the proposed adaptive suspension concepts. Realistic vehicle data and test terrain profiles may be used for conclusive results.

Development of microcomputer controller system for real-time implementation of proposed suspension control logic. A microcomputer in-the-loop real-time

simulator consisting of a hybrid computer military vehicle model interfaced to the microcomputer damper controller may be carried out to experimentally verify the potential ride improvement.

Construction of laboratory microcomputer controlled suspension concept models for complete hardware in-the-loop model simulation. The laboratory suspension models may be used for demonstrating and testing various adaptive suspension concepts. The experience acquired in one laboratory experiment will be invaluable for future implementation effort as well as for recognizing potential practical problems.

Study and investigation on current state-of-the-art sensor methodology for on-board measurements of vehicle states and terrain profile.

Study and investigation on current state-of-the-art suspension elements such as heavy-duty low-power-input variable dampers.

Development of in-house research capability for implementing and evaluating advanced adaptive suspension concepts. Close interaction with academic institutions and industries may be suggested for a quick buildup of such capability.

5.0. DISCUSSION

5.1. Preliminary Study

In September 1980, Francis Hoogterp issued a report "Preliminary Study for Adaptive Suspension System Program." It is included as Appendix A to this report. The first technical area it addressed was the need to sense terrain elevations at 1-foot intervals at speeds up to 50 mph (73 ft/sec). It was concluded that the distances involved are too short for radar, but a sonar reflective sensor made by Polaroid might be modified to meet this requirement. A pressure transducer located within a hydropneumatic type suspension unit or an accelerometer mounted on a roadarm near the roadwheel could also be used to sense terrain elevations. For all of these three schemes, a hull-mounted accelerometer would also be needed to remove the effect of hull vertical motion.

Assuming the terrain elevation can be sensed at 1-foot intervals, the next step is to compute the RMS and perhaps frequency content of the terrain. Mr. Hoogterp suggests that one high pass and three low pass digital filters implemented on a 16-bit microprocessor could be used to meet this requirement.

The Environmental Research Institute of Michigan (ERIM) is developing a laser-based terrain previewing system for the Department of the Army Advanced Research Projects Agency. It will have a 40° field of view in azimuth and elevation, a ranging accuracy of ±3mm RMS, operate on 7mw of laser power, have a 30-foot look-ahead capability, and fit in a 4-inch cube. It is intended for use on a slow-moving hexapod "walking machine". ERIM seems

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to have the expertise to modify this system for vehicle ride purposes and to process the acquired data signals in order to characterize the terrain. The cost for a prototype unit would most likely exceed $100,000.

5.2. Terrain Characterization Methods for Microcomputers

5.2.1. Introduction

Since a knowledge of the terrain would be an important input to a controllable suspension system, digital computer experiments were conducted to determine the potential of digital filters for identifying the overall roughness and the frequency content of terrains.

This effort started with the assumption that the terrain elevation could be sensed at 1-foot intervals and converted to a digital value and made available to the computing algorithm. The goal was then to find mathematical methods, suitable for microprocessor implementation, which can detect both the roughness and frequency content (wavelengths) of the terrain.

5.2.2. Digital Filtering Techniques

The main advantages of digital filtering over the more standard mathematical methods (such as Fourier transforms) are:

o much smaller computer memory requirements;

o much faster computation time (to permit real-time performance);

o updating of terrain parameters on a continuous (on the order of once per foot) basis rather than on an occasional (once per 250-500 foot) basis.

The disadvantages are some loss of accuracy in the overall RMS and much less detail in distinguishing component frequencies. However, for the purpose of this project, a 5% RMS error would be acceptable and it is only necessary to identify the one or two regions of the frequency spectrum which typically account for most of the terrain roughness.

Digital filters were designed to compute the overall RMS of a terrain elevation input signal and to compute RMS values of the terrain from four different frequency regions. The frequency regions were defined by the period of the waveform being 2 to 10 feet, 20 to 40 feet, and 40 to 80 feet. Waves shorter than two feet cannot be detected with a 1-foot sampling interval, while waves longer than 80 feet do not appreciably influence ride quality for the range of vehicle speeds being considered.

The first filter design considered was a system of Butterworth type high pass and band pass filters of fourth order implemented in 60-bit floating point arithmetic. The cut-off frequency of the high pass filter was set at 1/80 Hz. in order to filter out wavelengths greater than 80 feet. The root mean square (RMS) value of the high pass filtered signal, Yi, was computed as:

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N} y_i^2}$$

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where N=512. This was considered to be the overall RMS of the signal as shown in Table 5-1.

The original signal was also filtered using the four pole band pass filter with the cut-off frequencies set for 80- and 40-foot waves. The RMS of this filtered signal is designated in Table 5-1 as the "80-40" foot RMS of the signal. By setting the desired cut-off frequencies in the band pass filter, the same method was used to compute the "40-20" foot RMS and the "20-10" foot RMS of the input signal. Finally, the high pass filter with the cut-off frequency set at 1/10 Hz. was used to compute the "10-0" foot RMS.

This system of digital filters was tested to determine its ability to identify the frequency of a simple sine wave with a ±12-inch amplitude. Several frequencies were input (one at a time) near the center and at the edge of the frequency bands. The results are shown in Table 5-1.

Table 5-1. Four-Pole Butterworth Filter Results (60-Bit Arithmetic)

Input Wavelength	Overall RMS	80-40	Computed 40-20	RMS 20-10	10-0
4	8.485	5.837	.003	.008	8.485
8	8.485	1.996	.016	.918	7.936
10	8.496	.205	.051	6.002	6.002
14	8.477	.554	.376	8.480	2.007
20	8.466	.630	6.547	5.386	.393
28	8.478	.401	8.521	.463	.122
40	8.421	5.964	5.964	.712	.029
56	8.277	8.433	.454	.012	.008
80	5.985	6.019	.524	.032	.0026
119	1.672	.299	.009	0	0

The theoretical RMS of each of the signals is 8.485 inch. Note that for an 80-foot period, the overall RMS is only 5.985. This is the result of the 80-foot cut-off frequency in the high pass digital filter, which is expected to reduce the amplitude of an input wave at the cut-off frequency by 3db (i.e., multiply it by $\sqrt{2}/2$). The amplitude reduction for the 119-foot wave is much greater as shown by the total RMS value of only 1.672. Whenever the actual period is in the center of one of the digital filter pass bands, the signal frequency is very strongly identified with that band alone. For

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instance, for a 28-foot input wavelength, Table 5-1 shows an RMS value of 8.521 in the "40-20" foot region. When it is at the boundary of two adjacent pass bands 0.707 of the total signal RMS is assigned to each pass band.

If it is desired to always characterize the terrain by a single frequency waveform, then a scheme could be readily devised to estimate the frequency and amplitude of the wave from the values produced by this system of filters (for example, as the maximum value of a parabola computed to fit the four RMS vs. frequency values). The "80-40" foot band pass filter seems to have some problems with wavelengths of less than 10 feet, and therefore, requires more investigation. The sampling interval of one foot may be responsible, and it probably also accounts for the scatter in the rest of the table entries.

The previous digital filtering results were achieved on a 60-bit computer. Since digital filtering is known to be sensitive to the number of digits used in the computations, these filters were also tested on a computer operating with 32-bit floating point arithmetic. The high pass filtering was done with a four-pole Butterworth high pass digital filter. A four-pole Butterworth band pass filter was tried for the required band pass filtering, but it did not function properly because of the 32-bit word size. This problem was overcome by applying a two-pole Butterworth band pass filter to the signal two times in succession.

As was done with the 60-bit filters, a number of computer runs were made with artifically constructed input signals. This was done so that the RMS values produced by the program in each of the four frequency intervals could be compared with the theoretical values of the input signal.

The results as displayed in Table 5-2 show that when only a single frequency wave is present and is at the center of one of the four frequency intervals, it usually results in the RMS value for the proper frequency interval being about nine times as high as for any other of the frequency intervals. When the frequency of the input wave is at the boundary of two frequency intervals, equal RMS values result in these two intervals, and the RMS in the two remaining intervals is lower by more than a factor of ten. For wavelengths of less than 80 feet, the overall RMS of the terrain is related approximately to the four frequency filtered RMS values by:

$$RMS^2_{TOT} = RMS^2_{80-40} + RMS^2_{40-20} + RMS^2_{20-10} + RMS^2_{10-0}$$

This can be seen in both Tables 5-1 and 5-2.

For the four frequency intervals studied in Tables 5-1 and 5-2, let the signal-to-noise-ratio be defined as the result of dividing the calculated RMS value which is closest to the input wavelengths by the largest calculated RMS value among any of the other wavelengths. The signal to noise ratios calculated from the values displayed in Tables 5-1 and 5-2 are shown in Table 5-3.

The overall results of this section show that this type of filtering scheme can identify the various wavelengths present in a terrain, even when a 32-bit computer is used.

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Special provisions were made in the 32-bit general purpose computer program to simulate the effect of 16-bit integer microprocessor arithmetic. With this scheme, the double application of the four-pole Butterworth band pass filters showed a tendency toward instability and erratic results. However, the two-pole filters applied four times to a single frequency sine wave produced the results shown in Table 5-4. The RMS value at the middle of the frequency interval is within 2% of its theoretical value. However, the edge values are 31% lower than for the four-pole filter applied twice. Theoretically, the RMS at the edge should be $\sqrt{2}/2$ times the center RMS. This enables the total RMS of the signal to be computed from the RMS in two neighboring intervals. Thus, the edge values in Table 5-4 (for the 20- and 40-foot wave) are about 30% lower than ideal. However, the filter coefficients could be adjusted to rectify most of this problem.

All the computations described above have been carried out on fixed sets of numbers of length 512. As a vehicle is traversing terrain, any such array of terrain elevations would need to be updated at every sample interval by adding the most recent elevation, deleting the oldest, and recomputing the RMS values. A more practical approach is to submit each new terrain elevation to the digital filters in order to produce four filtered terrain signals. For each of these signals, an N-point running average mean square (MS) value can then be computed using the formula:

$$MS_t = \left[Y_t + (N-1)MS_{t-\Delta} \right]/N$$

N should be chosen consistent with the frequency of the filter which produced Y from the terrain elevation. This method produced instantaneous RMS values corresponding to a recently traversed section of terrain whose length is determined by N. This method was tested in 32-bit arithmetic and produced accurate and non-oscillatory results as long as N was longer than the longest wavelengths in the filtered terrain elevation signal.

5.2.3. Running Average/Predominant Period Technique

The data displayed in Table 5-5 are the result of estimating the single predominant frequency in a data signal by a means other than digital filtering. Running average values are computed continuously over the most recent 50-foot interval for the RMS values of the terrain elevation (RMSE) and the terrain slope (RMSS). An estimate for the length or period, P, of the most predominant waveform present in the terrain is then computed by:

$$P = 2\pi \ RMSE/RMSS$$

The development of this formula is documented in Reference 1. The range of values obtained in Table 5-5 is due to the 50-foot running average effect, and perhaps a longer average should be used. The mathematical development of this method is documented in Reference 1. The running average computation can be efficiently carried out by the following scheme:

    (1) Let x_i be the i_{th} data value.

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Table 5-2. Two-Pole Butterworth Filter Applied Twice (32-Bit Arithmetic)

Input Wavelength	Computed RMS 80-40	40-20	20-10	10-0	Total RMS
3.5	.001	.000	.008	8.477	8.485
10	.005	.123	6.103	6.002	8.496
14	.024	.837	8.480	2.007	8.477
20	.133	6.036	5.994	.479	8.476
28	.853	8.521	.997	.122	8.478
40	6.038	6.033	.143	.029	8.421
56	8.428	.986	.029	.008	8.277
119	.670	.021	.001	.000	1.672

Table 5-3. Digital Filtering Signal-to-Noise Ratios

Input Wavelength	60-Bit Arithmetic Signal-to-Noise Ratio	32-Bit Arithmetic Signal-to-Noise Ratio
10	41.41	69.59
14	4.23	4.23
20	*	17.76
21	13.46	*
28	18.40	8.55
40	11.85	59.69
56	18.57	8.55
80	11.49	*

*Not Available

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Table 5-4. Two-Pole Butterworth Band Pass Filter Applied Four Times, 16-Bit Integer Arithmetic

Period	40-20 RMS
3.5	.000
10	.240
14	1.049
18	2.962
20	4.347
22	5.858
24	7.255
28	8.383*
32	7.464
36	5.676
40	3.967
42	3.283
56	.872
80	.076
119	.000

*Theoretical = 8.4385

TABLE 5-5. Frequency Estimation By Running Average Method

Actual Period	Estimated Period
8	8.1-8.4
10	10.0-10.4
14	13.8-14.5
21	20.4-21.7
28	26.8-29.4
40	39.2-40.8
56	51-61
80	72-89
119	101-140

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(2) Compute $A = \dfrac{1}{50} \displaystyle\sum_{i=1}^{50} x_i$

(3) For x_{51}, compute $A = \dfrac{1}{50} [50A - x_1 + x_{51}]$, and store the value of

x_{51} in x_1.

(4) For x_{52} thru x_{100}, let the index i range from 52 to 100 and compute:

$A = \dfrac{1}{50} [50A - x_{i-50} + x_i]$, and store the value of x_i in x_{i-50}.

(5) For x_{101} thru x_{150}, continue the process as in steps 3 and 4, but use x_{101} thru x_{150} in place of x_{51} thru x_{100}.

These preliminary studies show that properly devised digital filtering and other signal processing techniques can be used to assess the overall roughness of a terrain and its wavelength composition. They indicate that a 16-bit digital microprocessor should be sufficiently accurate to obtain the desired results. Actual implementation on microprocessor hardware will be required to determine if the computations can be done fast enough for on-board vehicle operations. This discussion in Section 5.3. addresses this question.

5.3. Design and Microprocessor Implementation of Digital Filters

Dr. K. C. Cheok and Dr. N. K. Loh of Oakland University have completed a comprehensive and technically in-depth study entitled, "Design and Microprocessor Implementation of Frequency Selective Digital Filters for Application to Terrain Roughness Identification," Reference 2. The theoretical and mathematical basis for analog and digital signal filtering was thoroughly reviewed and carefully applied to the terrain roughness problem. Technical problems such as frequency warping, distortion, and aliasing can occur because of the discrete sampling of the signal and the number of digits (or bits) available in microprocessor arithmetic. Methods to avoid or overcome these problems were incorporated into the filter design process, taking into account the characteristics of the particular microprocessor to be used—the Motorola MC6802. Successful implementation on the microprocessor required development of fast and accurate arithmetic subroutines, the scaling of the recursive digital filter equations, the special handling of arithmetic saturation, and careful attention to memory management.

A laboratory set up was created at Oakland University in order to observe the actual performance of the total digital filtering system. The experimental results generally agree well with the theoretical predictions, though there are minor discrepancies which can be remedied through further fine adjustments in the set-up. The system demonstrates sufficiently fast computational speed and adequate accuracy for use in the identification of terrain frequencies.

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5.4. Optimum Constant Damping Level as a Function of Terrain

It has long been observed from both vehicle field testing and computer simulation that a higher level of damping can improve vehicle ride on rougher terrains while giving a poorer ride on smoother terrains, and vice-versa. Thus, vehicle damping design is usually a compromise aimed at moderate or average terrain roughness conditions. One of our major goals was to find a method for predicting optimum damping as a function of terrain roughness and/or frequency content in a way which could be implemented in real-time using an on-board microcomputer.

One method of accomplishing this goal is documented in this section. It involves simulating the LK10934 (a 20-ton tracked combat vehicle concept) over nine different terrains using the TACOM-validated VRIDE computer model, Reference 3. On each terrain the level of damping (or damping factor), was determined which allowed the vehicle to achieve the highest speed at the ride-comfort limiting level of 6 watts driver vertical absorbed power. This method of measuring ride comfort is in Army-wide use and is documented in Reference 4. Damping was varied by multiplying the entire force vs. velocity curve by a constant factor. A given level of damping and a constant vehicle speed were maintained for each run over each course.

Terrain RMS roughness varied from 0.67 to 3.88 inches, vehicle speeds ranged from 15 to 85 mph, and the optimum damping level varied from 0.4 to 1.4 times nominal damping. As shown in Figure 5-1, the optimum damping level produced an increase in speed of as much as 38 mph on one of the smoothest courses and as little as 0.3 mph on one of the roughest courses. This implies that the nominal damping level is a good design value for the rougher terrain.

Figure 5-2 shows the optimum damping factor and its least squares regression line as a function of terrain RMS. If the equation of the regression line were used to predict the optimum damping factor from the terrain RMS, then the maximum error would be 0.38, the average would be 0.12, and the root mean square (RMS) error would be 0.18. This amount of error (especially the 0.38 maximum value) could result in a rougher vehicle ride over some terrains than using the nominal damping level.

In order to find a better predictor of the optimum damping level, the terrains were frequency analyzed using digital filter techniques as described in Section 5.2. of this report. The RMS of each terrain attributable to various wavelengths is shown in Table 5-6. This type of terrain analysis could be done in real-time if the terrain elevation could be sensed and fed into an on-board microcomputer. Since the LK10934 concept was designed to have a bounce natural frequency of 68 cycles per minute, there will be a diminishing effect of those wavelengths which require more than 0.88 second for the vehicle to traverse to a given speed. Thus, an "effective RMS" value was computed for each terrain as the square root of the sum of the squares of all the RMS values in Table 5-6, summing from zero to the first frequency band whose wavelength mid-point in feet exceeded 1.0 times the vehicle speed in ft/sec. This square root of the sum of squares

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Table 5-6. Terrain Roughness Analysis

Course	W. E. S. RMS (in)	80-0 Total RMS (in)	Range of Wavelengths (Ft.)							Variability Factor
			80-40	56-28	40-20	28-14	20-10	14-7	10-0	
APG-31	3.94	5.48	2.88	3.24	3.69	2.42	1.11	0.55	0.38	1.29
FTKN78A	3.39	4.50	1.75	3.08	3.67	1.75	0.87	0.57	0.44	2.29
FTKN910	2.24	3.16	1.21	2.36	2.46	1.17	0.49	1.25	0.26	1.28
APG-29	2.13	2.96	1.10	1.88	2.17	1.42	0.88	0.65	0.50	1.10
FTKN56A	1.73	2.35	1.09	1.34	1.70	1.05	0.65	0.56	0.50	2.00
APG-11	1.33	1.73	0.87	1.05	1.07	0.88	0.49	0.33	0.44	1.37
APG-9	1.08	1.37	0.68	0.58	0.83	0.76	0.49	0.38	0.37	1.28
FTKN12A	0.70	0.89	0.41	0.49	0.51	0.35	0.37	0.31	0.27	1.30
APG-37	0.60	1.04	0.67	0.81	0.50	0.26	0.20	0.12	0.17	1.60

technique is used instead of simple summing because of the way in which the digital filtering distributes the amplitude of a signal whose frequency is near the edge of one of the wavelength bands. Figure 5-3 shows the optimum damping factor and its least squares regression line as a function of the speed normalized or "effective" RMS. This regression line can predict the optimum damping factor with a maximum error of 0.19, average error of 0.10, and RMS error of 0.13. This improved level of predictability compared to using the usual terrain RMS shows that there is a definite potential for determining the optimum damping level as a function of terrain roughness and frequency content.

The lengths of the nine terrains used for these investigations were from 300 to 500 ft. If the roughness level or frequency content of a terrain changes significantly, then the optimum damping level also changes. A measure of the variability of the nine sample terrains was obtained by computing the elevation RMS over several 200-foot long segments of a terrain and then dividing the maximum RMS value by the minimum RMS value obtained. The individual RMS values were calculated from 1 to 200 feet, 11 to 210 feet, 21 to 220 feet, and so on, until the end of the course. If the course is uniformly rough, then the variability factor computed by this method would be 1.0. For the nine terrains used here, the variability factor shown in Table 5-6 ranged from 1.10 to 2.29 with an average of 1.50. Thus, it seems that continuously adjusting the damping level as a function of varying terrain roughness and frequency while traversing a course should allow for higher speeds than using any single damping level. However, to implement this on the computer would require considerable effort including the addition of digital filtering techniques and other features into the VRIDE computer program. This has not yet been done.

5.5. Damping Control Based on Pitch Rate

Because of the problems involved with on-board terrain measurement and its present early development state, it was decided to investigate the potential for ride improvement based only on a knowledge of the vehicle motions. In particular, the pitching motions of the vehicle are readily measureable with modern instrumentation. In 1975, Dr. R. Beck and R. Salemka (Reference 5) reported success in simulating the reduction of average pitch rate by rapidly switching damping blow-off level between 1.5 nominal and 0.16 nominal as a function of pitch direction (that is, up or down). However, the effect on absorbed power was not reported. It is shown below that moderate success in reducing absorbed power can be achieved by making a relatively slow but continuous change in damping as a function of the time history of vehicle pitch rate.

Computer runs with some additional output variables implemented in VRIDE have shown that instantaneous pitch rate fluctuates much more rapidly than is desirable for a system control variable or for indicating the RMS level of the terrain (See Figure 5-4). The following formula, which is similar to a first order lag, was added to VRIDE to produce a running average value of pitch rate:

$$\dot{\theta}_a = \frac{|\dot{\theta}| + (T_cN - 1)\,\dot{\theta}_a}{T_cN}$$

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where $\dot{\theta}$ is the instantaneous pitch rate, $\dot{\theta}_a$ is the running average (filtered) pitch rate, T_c is the desired time constant, and N is the number of times per second that $\dot{\theta}$ is monitored and $\dot{\theta}$ is updated. After looking at $\dot{\theta}_a$ resulting from various values of T_c in VRIDE runs, it was decided to use T_c = 4 seconds. This caused the amplitude of the pitch rate $\dot{\theta}_a$ to be lower by almost a factor of 2 compared to the unfiltered signal. (Figure 5-5).

It was decided to adjust the damping rate (i.e., adjust orifice area of the damper) as a function of averaged pitch rate, $\dot{\theta}_a$, in the general manner as sketched below.
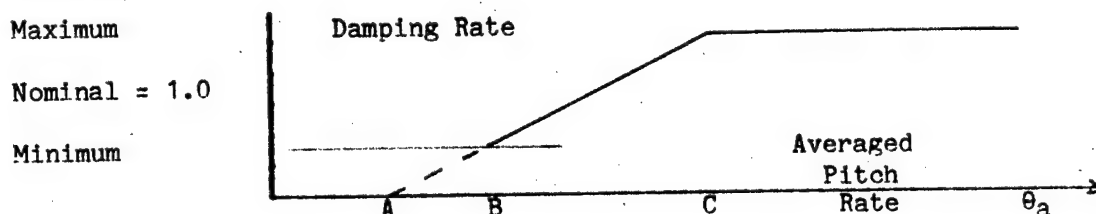
A relatively large number of iterations were required to obtain an adaptive suspension control scheme of the type outlined above which would improve the ride of the LK10934 on most terrains and not appreciably worsen it on any. Optimizing this control scheme requires determining the optimum values of four variables: the minimum and the maximum damping levels, and the slope and the x axis intercept of the straight line which transitions from the minimum to the maximum value. After many iterations, the final values chosen for these parameters are: minimum value .667, slope 1.667, y intercept 0.0, and maximum value 4.0. $\dot{\theta}_a$ was measured in rad/sec. The results obtained for the LK10934 concept vehicle are:

		6 Watt Speed (MPH)	
Terrain	RMS	Standard Suspension	Adaptive Suspension
APG-37	.68	51.0	62.3
APG-9	1.04	27.4	43.0
APG-11	1.32	28.2	33.2
APG-29	2.17	19.8	20.0
APG-31	3.88	13.1	14.3

This control scheme was rudimentary in that it worked with only the single input variable $\dot{\theta}_a$. Pitch acceleration or road arm position might also be very useful control parameters. Nevertheless, substantial increases were demonstrated in the vehicle's 6-watt speed. Better results are likely with more sophisticated control laws.

The relatively small improvements produced by the current control scheme on the higher RMS terrains seem to be due to a requirement for high damping on

these terrains even when the pitch rate is temporarily low. Once lowered by the control scheme, damping is not increased until after pitch rate has increased and thereby already adversely affected ride quality. Variable damping as a function of spring deflection is already available for automobile shock absorbers. A few VRIDE runs were made trying out this technique, but no immediate success was achieved. However, damping variation as a function of spring deflection in combination with pitch rate seems like a promising area for future investigation.

The amount of effort required to obtain the adaptive control scheme for the LK10934 points out the need for a more organized approach or a well-defined method for adaptive control law design. For some particular terrain with a relatively constant RMS value over its entire length, the 6-watt speed of the vehicle could be determined using VRIDE with different constant damping levels. Enough runs would be made to determine the optimum value for fixed damping. This process could be repeated for terrains covering the 0.5 to 4.0 inch RMS range. The average value of the running average pitch rate would be recorded for each run. When the entire process was completed, there would be available a table of optimum constant damping factor versus terrain RMS and average pitch rate. From this table, the parameters could be determined for the type of control scheme applied to the LK10934 simulation. Since a terrain RMS is typically not constant over its entire length, and since the four second running average pitch rate has been observed to fluctuate from 0.3 to 2.0 times its average value during the course of a single VRIDE run, it is expected that fine tuning of the control scheme would still be required.
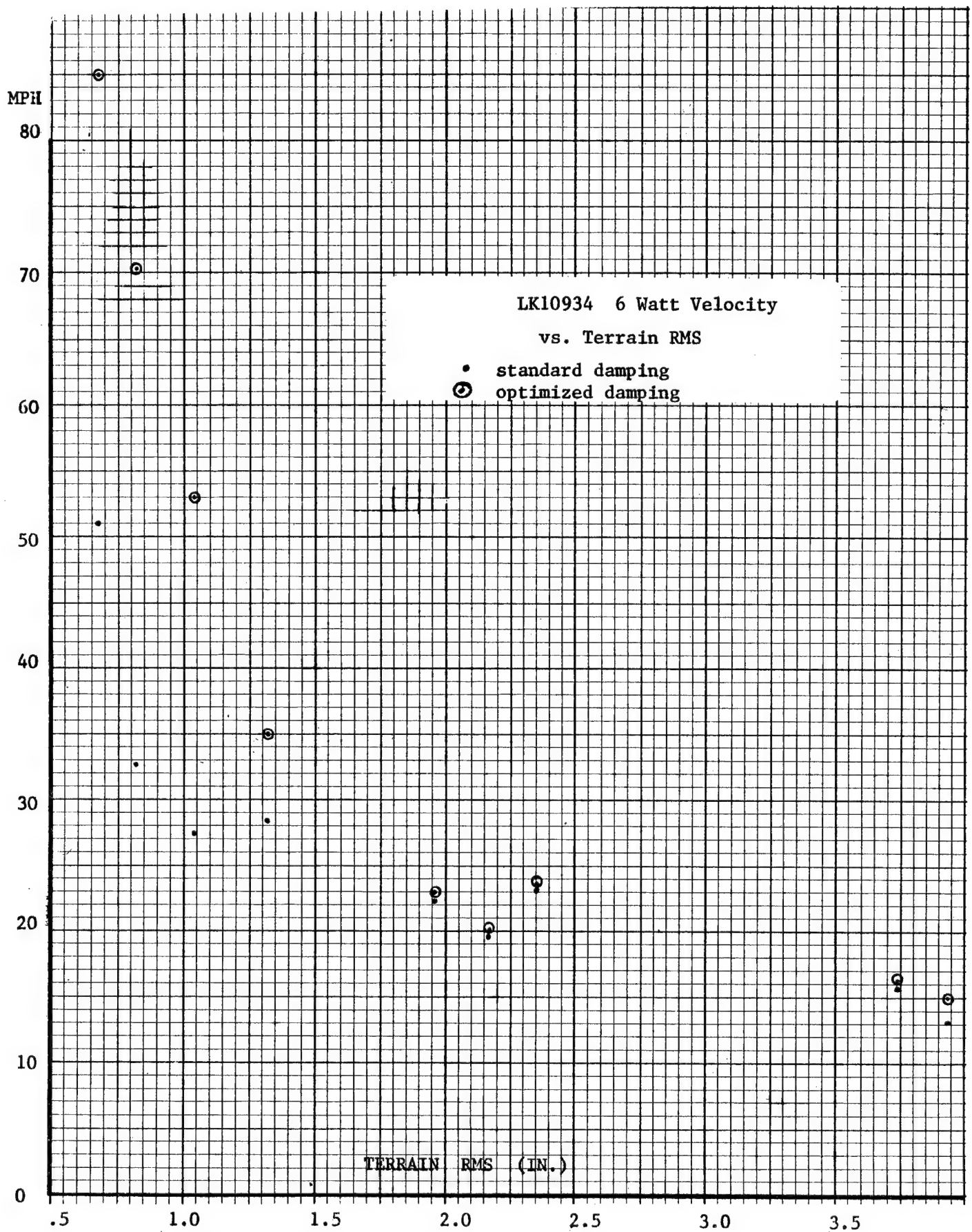
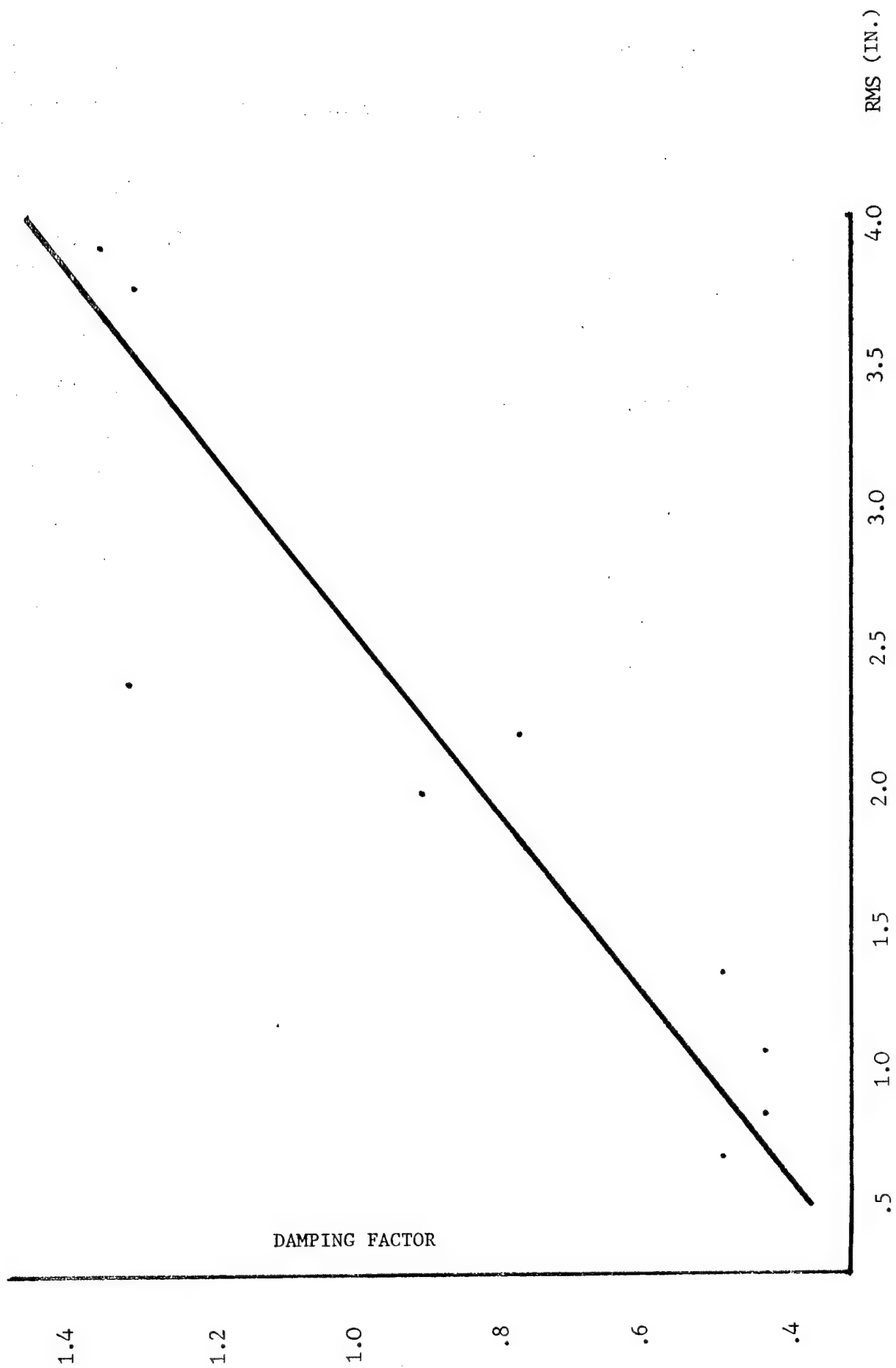Figure 5-1. LK10934 6-Watt Velocity Vs. Terrain RMS

Figure 5-2. Optimum Damping Factor at 6 Watts Vs. RMS
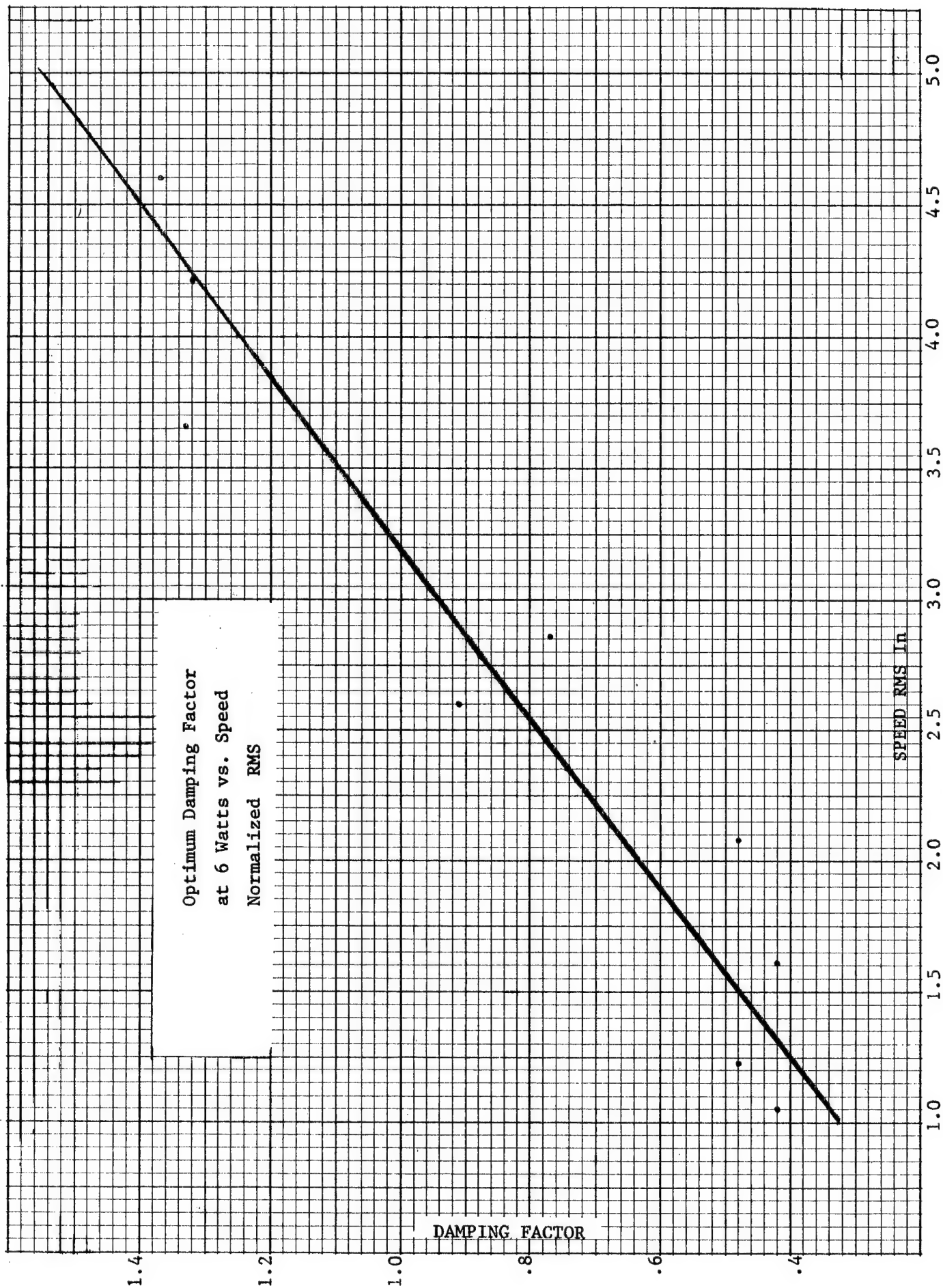
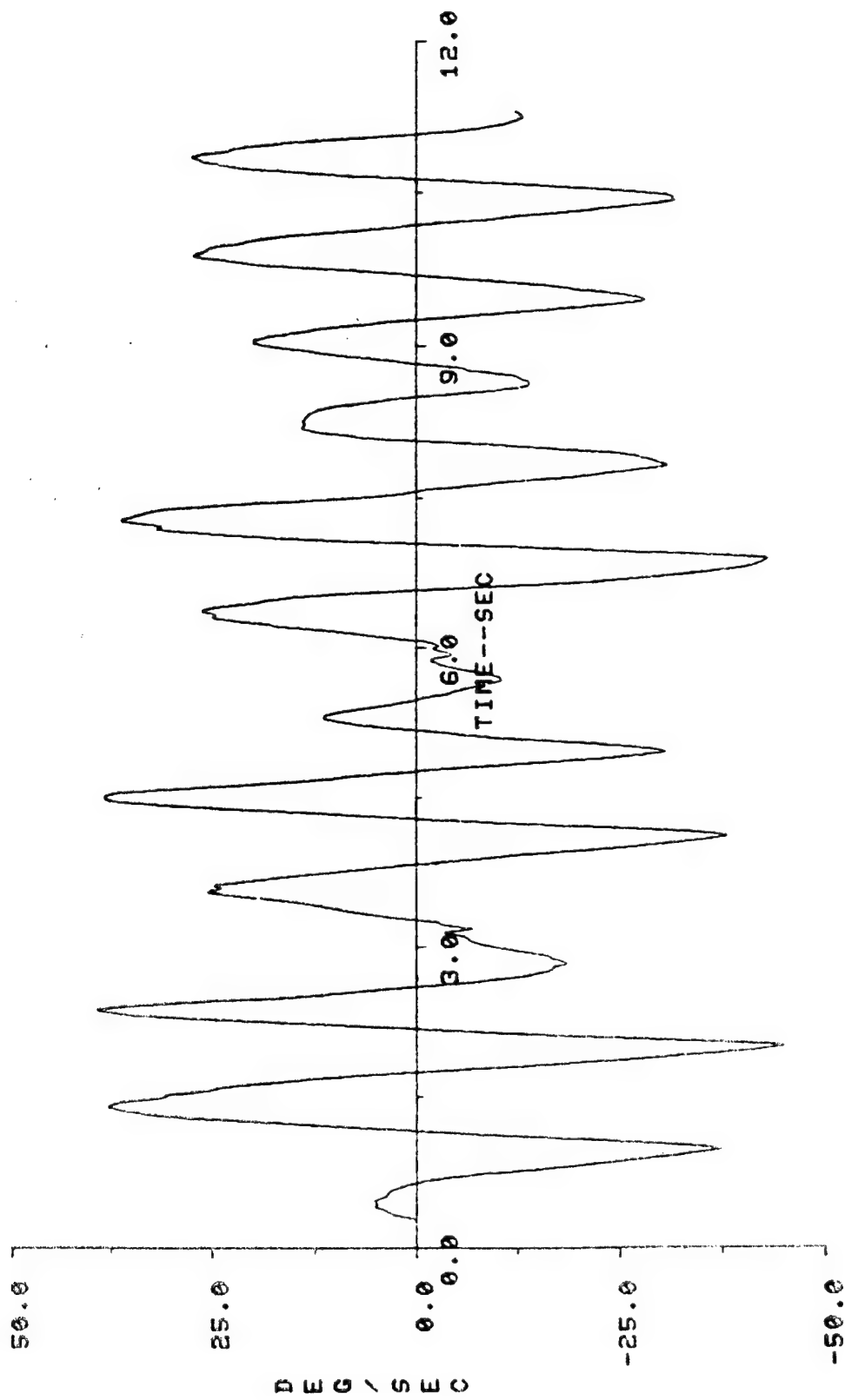Figure 5-3. Optimum Damping Factor Vs. Speed Normalized RMS

33

Figure 5-4. VRDRAV7 LK10934, 19.0 MPH, APG 29 (2.17 in. RMS)--Pitch Rate.
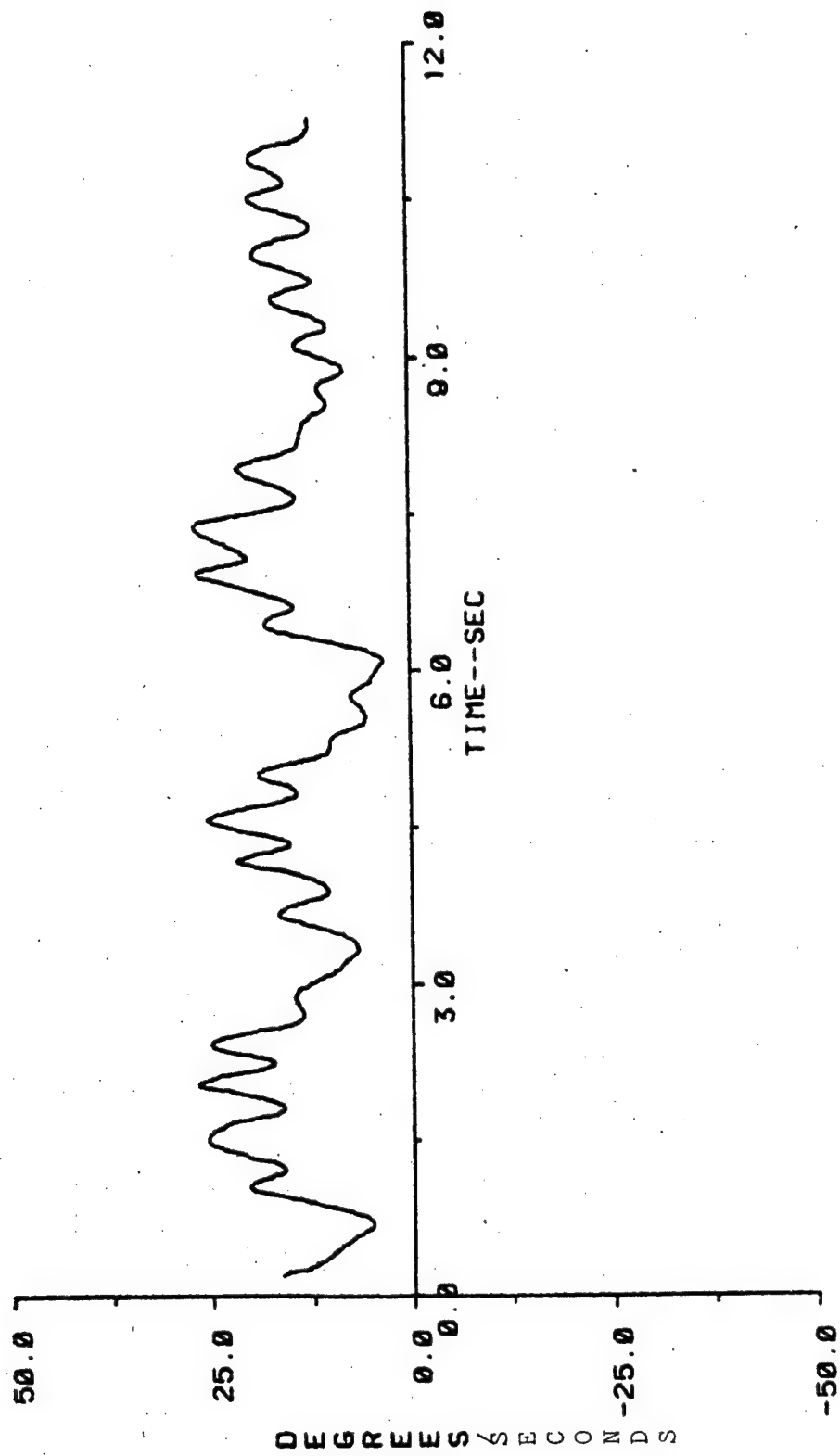
34

Figure 5-5. VRDRAV7 LK10934, 19.0 MPH, APG 29 (2.17 in. RMS)--Running Average Pitch Rate.

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5.6. Application of On-Off Passive Dampers To a Multiple-Wheeled Vehicle

This section presents the simulation results obtained from the application of the concept of on-off passive dampers (Reference 6,7) to a ten-wheeled test vehicle. It is shown that improvement in the vehicle ride performance over a typical test terrain is possible using the on-off passive dampers in lieu of the conventional dampers.

For continuity in the presentation, a simple vibration isolation system with a conventional damper is described below. The on-off passive damper is introduced afterward.

The concept of the on-off passive damper is then applied to the centered center of gravity (cg) configuration of the ten-wheeled HIMAG test bed vehicle. The performance of the on-off passive damper vibration isolation scheme was simulated in the VRIDE computer model. The results are documented below.

The differential equations of motion of a conventional suspension system that is, for a mass, m (acted on by a linear spring and damper) is given by:

$$m\ddot{x} = -b(\dot{x} - \dot{x}_0) - k(x - x_0) \tag{1}$$

where k and b are respectively the spring constant and the damping coefficient. A state space representation of (1) is given by:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -b/m \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ +k/m & +b/m \end{bmatrix} \begin{bmatrix} x_0 \\ \dot{x}_0 \end{bmatrix} \tag{2}$$

The values of k and b are usually chosen to provide the desired damping ratio or the desired resonant frequency ω_n.

An operational diagram and a control logic for a simple on-off passive suspension system (References 1 & 2) are shown in Figures 5-6 and 5-7. The control variable of the system is the adjustable damper coefficient b(t). The variable damper is assumed to be controlled by a high band-width damper orifice actuator.

The equation of motion for the on-off passive damper system shown in Figure 5-6 is given by:

$$m\ddot{Z} = k(Z - Z_0) - b(t)(\dot{Z} - \dot{Z}_0). \tag{3}$$

As shown in Figures 5-6 and 5-7, the coefficient b(t) takes on the constant value b or 0 depending on whether Z and $(Z - Z_0)$ are of the same sign or not. That is:

$$b(t) = \begin{cases} b, & \text{for } \dot{Z}(\dot{Z} - \dot{Z}_0) \geq 0; \\ 0, & \text{for } \dot{Z}(\dot{Z} - \dot{Z}_0) < 0. \end{cases} \tag{4}$$

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A state space equation for (3) may be written as:

$$
\begin{bmatrix} \dot{Z} \\ \ddot{Z} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -k/m & -b/m \end{bmatrix} \begin{bmatrix} Z \\ \dot{Z} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ k/m & b(t)/m \end{bmatrix} \begin{bmatrix} Z_o \\ \dot{Z}_o \end{bmatrix} \qquad (5)
$$

The on-off passive suspension system defined by equations (3)-(5) has been shown in References 6 and 7 to provide a desirable vibration isolation characteristic which filters out high frequency excitation inputs when applied to a mass supported by a single spring and damper. In this report, the logic described by eq. (4) is applied to a ten-wheeled vehicle which is simulated using a modified version of the VRIDE program (Reference 3) on the PRIME computer facility at the US Army Tank-Automotive Command in Warren, Michigan. In the simulation, the logic of eq. (4) is installed independently for each individual wheel suspension subsystem. The actual parameters of the center cg configuration of the HIMAG test bed vehicle were used. The VRIDE model has been extensively validated against field test data for this vehicle.

For purposes of suspension system evaluation, this vehicle was simulated running over a set of five Ft. Knox test courses which represent a range of quite smooth to very rough cross-country conditions. The vertical elevations of these courses were measured at 1-foot horizontal intervals. These values, with linear interpolations between data points, were used as a forcing function at the bottom of the roadwheels in the VRIDE model.
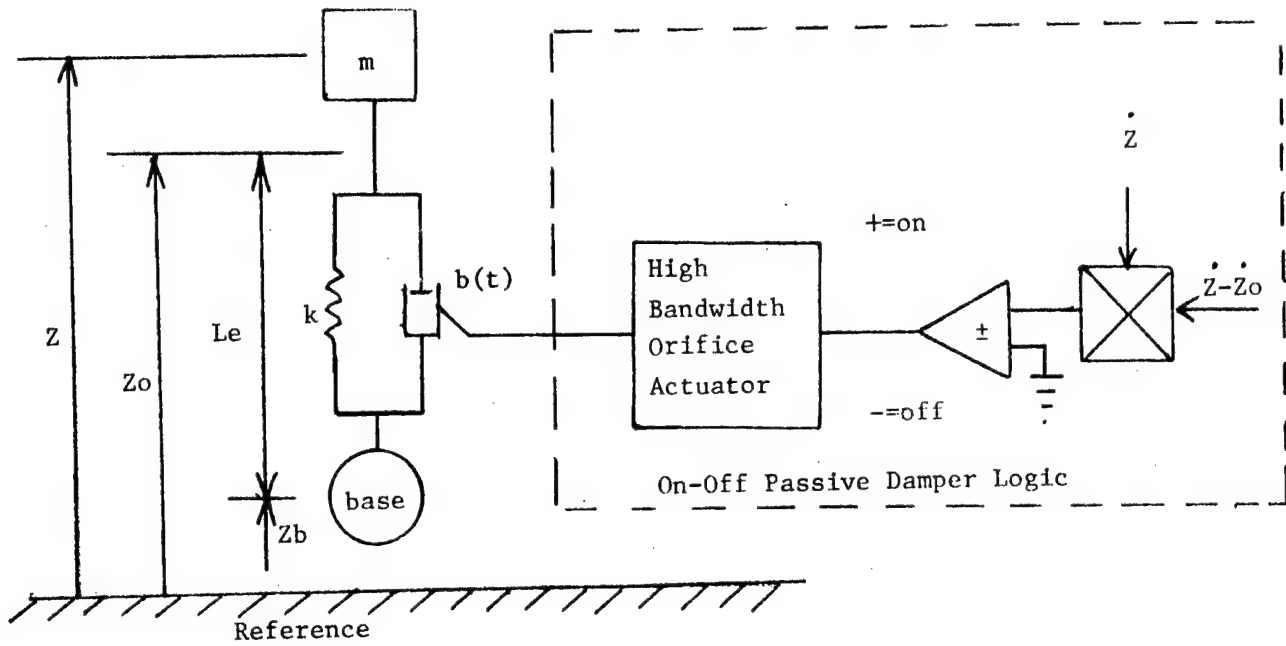
37

Figure 5-6. A Simple Vibration Isolation System
with a On-Off Passive Damper
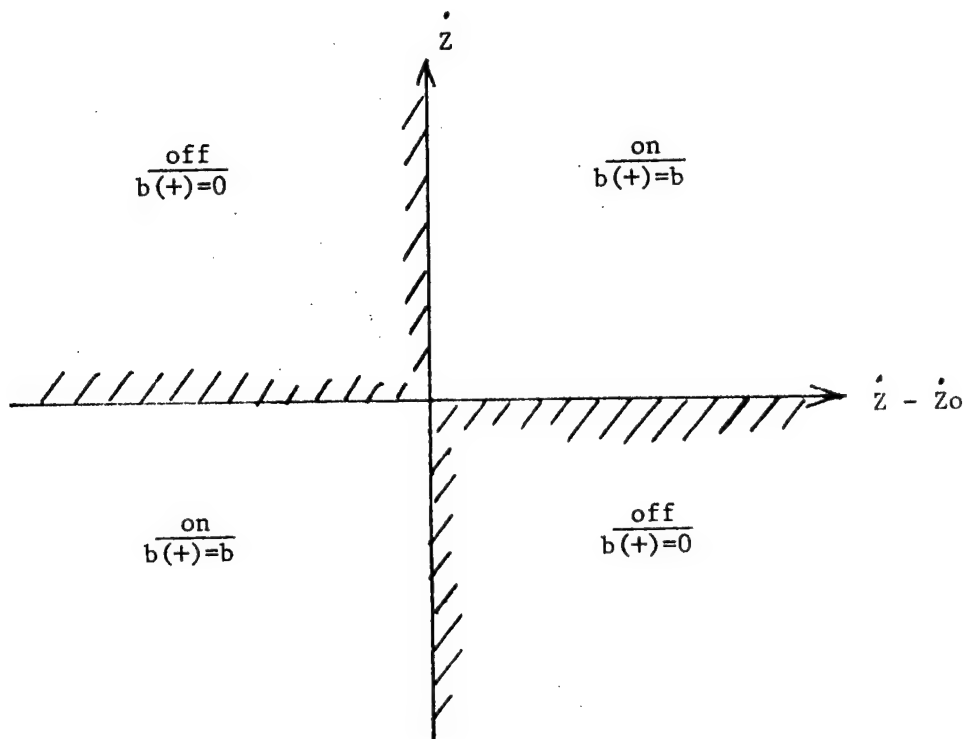

Figure 5-7. On-Off Passive Damper Logic

For comparison purposes, the simulation runs were carried out with:

   (I)   the vehicle having conventional dampers;

  (II)   the vehicle having the on-off passive dampers (logic of equation 4);

 (III)   the vehicle having the on-off passive dampers (logic of equation 4)
          but with increased damper coefficient of 1.5 times its original
          values.

In the simulation, these vehicles were "test driven" over the simulated
terrains at various constant speeds. The performance of a vehicle is moni-
tored at speeds of 5, 10, ..., 70 mph. The list of monitored variables
includes the absolute values of θ max, $\dot{\theta}$ max, and $\ddot{\theta}$ max (maximum pitch
angle, velocity, and acceleration); θrms, $\dot{\theta}$rms, and $\ddot{\theta}$rms (RMS pitch angle,
velocity and acceleration), $\dot{y}$rms and $\dot{y}$max (RMS and maximum vertical velocity
at cg); $\ddot{y}$max (maximum vertical acceleration at cg; $\ddot{y}$ max and $\ddot{y}$ RMS
(maximum and RMS vertical acceleration of the driver) and the driver-
vertical-absorbed power, Pd.

A series of VRIDE runs was made comparing the on-off damper (II) to the
standard HIMAG damper (I) on the five Fort Knox terrains. Improvement in
driver-absorbed power with the on-off dampers was shown on all the courses.
On the average, for any given speed, the driver-absorbed power was reduced by
almost 50% on the smoother courses and by at least 15% on the rougher cour-
ses. The speed at which 6 watts was reached increased by more than 20 mph
on the smooth courses and less than 1 mph on the roughest courses.

For the median roughness course (.173 in. RMS), plots were made of several
vehicle outputs vs. speed. These show that the two damping systems per-
formed basically the same in terms of maximum pitch angle, maximum pitch
rate, and RMS pitch angle. The on-off damper was somewhat better in terms
of maximum pitch acceleration, RMS pitch rate, and maximum vertical acce-
leration of the driver, and in RMS vertical velocity of the cg. In terms
of maximum and RMS vertical acceleration of the cg and RMS pitch accelera-
tion, the on-off damper was definitely better, at times by as much as 30%.
When the on-off damper was better, it was consistently better for speeds in
the 5 to 70 mph range, (up to 12 watts). The driver-absorbed power vs.
speed plots are given below:

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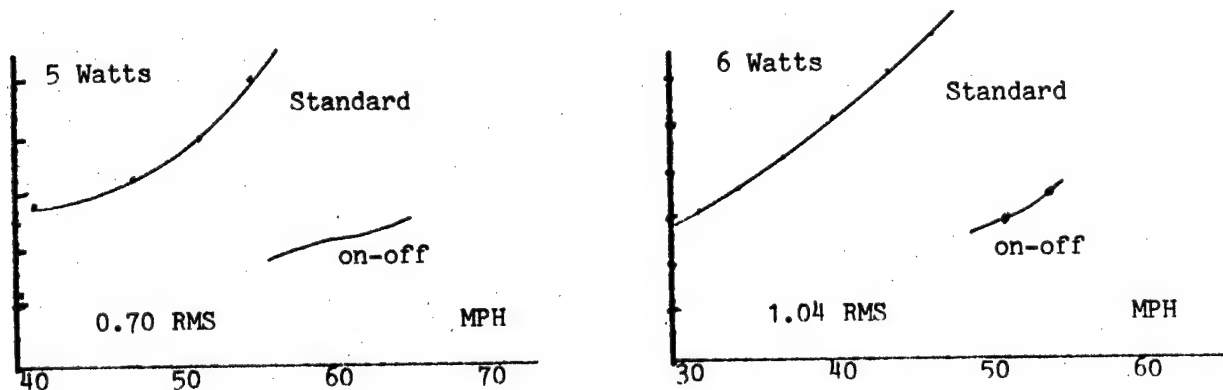
Since the on-off damper system (II) was just added on to an already designed damping system (I), it seems that even better performance might be obtained if the on-off effect was considered in the overall suspension design process. Since the on-off damper is "on" only when it tends to improve the ride, it seems that a higher level of damping might improve the ride even more. This might also give relatively more improvement on the rougher courses where it has not yet been achieved. For these reasons, damping system (III) was formulated with the damping level 1.5 times the nominal level and with the on-off control law. The HIMAG vehicle was simulated over test course FTKN910 (2.24 in. RMS).

For the test runs over this simulated terrain with the standard damping, the vehicle exhibits a distinct resonance characteristic over the range of 15 to 25 mph for driver-absorbed power; maximum pitch angle, pitch rate, and pitch acceleration; and RMS of pitch angle, pitch rate, and pitch acceleration. Also, maximum vertical acceleration at the driver and cg locations shows a very strong peak in the 15-25 mph range. The on-off damper system with the 1.5 nominal damping level shows a marked decrease in the resonance peak for all these variables.

In general, with on-off dampers, improvements in the simulated performance of the vehicle are obtained in all the monitored variables, when compared to standard dampers. Significant reduction in the resonance transmittivity are obtained in $|\theta|max$, $\dot{\theta}$ RMS, YRMS, $\dot{Y}$ RMS, $|\ddot{Y}|max$, $|\ddot{Y}^d|max$, $\ddot{y}^d$ RMS, and P_d. Superior high speed performance area achieved in terms of considerably reduced $\ddot{\theta}$ RMS, $\ddot{Y}$ RMS, $\dot{Y}$ RMS, and P_d (driver-absorbed power).

For the simulated vehicle with on-off passive dampers having increased damper coefficients of 1.5 times its original values, excellent reduction in the resonance transmittivity is found in all the monitored variables, as compared to the two previous cases. The high speed characteristics for the increased damping system are similar to those of on-off passive dampers in Case II. Due to the increased damping, very slight degradation in the high speed as well as low speed performance may be noticed in $|\dot{Y}$ RMS$|$, $|\ddot{Y}$ max$|$ $|Y^d max|$, $|Y^d RMS|$, and P_d. However, the decrease in the resonance peaks in the 15-25 mph range are much more noteworthy.

For clarity of presentation the improvement in the ride performance obtained from the simulation results are summarized in Table 5-7. Approximate improvement indices are included for ease of comparison.

The work described in this section is ongoing at Oakland University at the time of this report. However, it appears quite promising. The complete results will be described at a greater level of detail in a forthcoming contractor report.

Table 5-7. Improvement Chart of Ride Characteristics for Vehicle with On-Off Passive Dampers

		$|\Theta|_{max}$	$|\dot{\Theta}|_{max}$	$|\ddot{\Theta}|_{max}$	Θ_{RMS}	$\dot{\Theta}_{RMS}$	$\ddot{\Theta}_{RMS}$	$\dot{Y}_{RMS}$	$\ddot{Y}_{RMS}$	$|\dot{Y}|_{max}$	$|\dot{Y}^d|_{max}$	$|\ddot{Y}^q|_{max}$	Pd
Reduced Vibration Transmittivity at Resonance Speed (15 - 30 mph)	With on-off Passive Dampers	0	1	3	0	1	1	2	2	2	3	3	3
	With Increased Coefficient On-Off Passive Dampers	1	2	3	2	2	2	3	3	3	3	3	3
Reduced Vibration Transmittivity at High Speed (45 mph & over)	With on-off Passive Dampers	1	1	1	1	2	2	1	2	1	1	2	3
	With Increased Coefficient on-off Passive Dampers	1	1	1	1	2	2	1	2	1	1	2	3

Improvement Scale with reference to conventional damper vehicle system

0 = slight improvement (approximately 5% or less)
1 = moderate improvement (approximately 5-25%)
2 = significant improvement (approximately 25-50%)
3 = excellent improvement (approximately 50% or over)

41

REFERENCES

(1) "Investigation of Advanced Spectral Analysis Techniques", Proceedings of the 7th International Conference of the Society for Terrain-Vehicle Systems, August 1981, R. A. Daigle.

(2) "Design and Microprocessor Based Implementation of Digital Frequency Selective Filters for Application in Terrain Roughness Identification," TACOM Report No. 12688. April 1982, K. C. Cheok and N. K. Loh.

(3) "Interactive Vehicle Dynamics and Ride Evaluation Package," TACOM Report No. 12413, November 1978, Francis B. Hoogterp.

(4) "Theory of Human Vibration Response," presented at the Winter Annual Meeting and Energy Systems Exposition of the American Society of Mechanical Engineers, New York, NY, Nov 27 - Dec 1, 1966, Pradko, F., Richard, L., and Victor Kaluza.

(5) "Feasibility Analysis and Evaluation of an Adaptive Tracked Vehicle Suspension and Control System," TACOM Report No. 11893 (LL-146), June 1975, Robert M. Salemka and Ronald R. Beck.

(6) "Vibration Control Using Semi-Active Force Generator," Lord Corporation (LL-7004), M. J. Crosby and R. A. Harwood, Lord Corporation and D. Karnopp, the University of California, Davis, California.

(7) "The Experimental Performance of an On-Off Active Damper," Lord Corporation (LL-2140), E. J. Krasnicki, Lord Kinematics, Lord Corporation.

APPENDIX A

PRELIMINARY STUDY FOR ADAPTIVE

SUSPENSION SYSTEM PROGRAM

Preliminary Study for
Adaptive Suspension System Program

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Applied Rsch Func
Tk-Autmv Concepts Lab
September 1980

An overall Adaptive Suspension System Program Summary is included as Appendix I. Certain general requirements of this system are of particular concern here. Since the system must be capable of operating at speeds up to 50 mph and take profile measurements at least every foot, this imposes a minimum rate requirement of 74 samples per second. It should be noted also that at 10 mph the vehicle traverses only 73 feet in the 5 seconds allotted for system start up.

The complete sensor-processor design cannot be postulated until the results of the suspension optimization effort have been analyzed and the decision is made as to the manner in which the suspension system will be alterable. Much can and has been accomplished in the area of sensor specifications and processing requirements.

Since we hope to use the results of the T95 suspension optimization study to formulate the basis for our control choices, we have automatically constrained our system to process terrain profile data to obtain rms information and/or the frequency content of the terrain. The traditional method for characterizing terrain roughness is to calculate the rms (root mean square) of the profile. This is done, however, only after passing the profile measurements through a high pass filter with a cutoff frequency of 1/60 cycle per foot. This characterization ignores differences in the slopes of the terrain PSD's which depict the varying predominant frequencies which are truely present in different profiles.

One approach to processing the profile data would be to use an FFT (Fast Fourier Transform) algorithm to estimate the PSD. This approach has several drawbacks. An FFT on 300 or 400 points can take considerable computation time. Also each time it is to be updated, the computation must be restarted and all the data points must be available simultaneously.

Another approach would be to take the digitized signal and run it through several high pass and low pass filters simultaneously (see Figure 1).
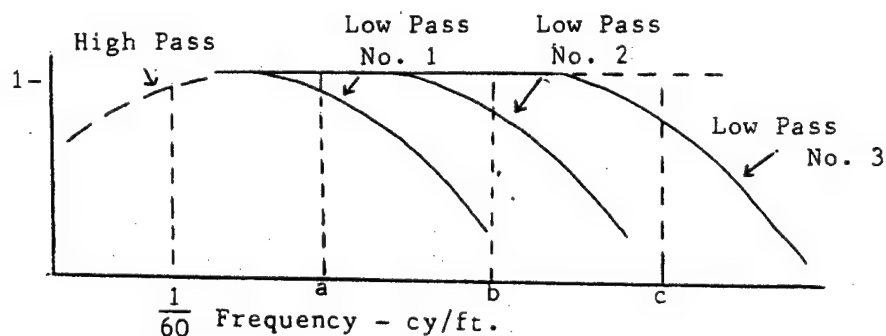

Figure 1

The output of each filter would be squared and averaged to give the mean square value of the filtered signal. The mean square outputs can then be differenced to obtain the mean square contribution between each two adjacent cutoff frequencies. The averaging of the mean squared signal can be performed with a time constant selected to average the most recent 4 or 5 seconds of data. In this way the data need not be stored and the output is continuously available. In other words the averaging need never be restarted in order to update the information required to control the suspension system.

This latter approach is definitely recommended for implementation. The number of filters required will probably be four unless an additional one is required due to high frequency noise. The recommended configuration is shown in Figure 2.

A couple of final notes should be made. Since the effort is to define the profile independently of the vehicle velocity the accelerometer signal should be digitized at a constant step size in feet. This can be accomplished by instrumenting the odometer to output a signal perhaps every 1/16 ft. of horizontal travel. This signal can then be used directly or counted down to obtain the digitizing signal remembering of course that the maximum sample distance acceptable is 1 foot. Also care must be taken to insure that the processor can keep up in the worst case situation (i.e. at 50 mph and with control changes to be made).

The filters described can best be implemented digitally. The transformation to the spatial domain is then achieved simply by maintaining a constant sample interval in feet. If the filter were implemented with analog components, either integration gains or cutoff frequencies would have to vary with the vehicle velocity. This would greatly complicate the design.

The adaptive suspension system implementation will definitely require a 16 bit microprocessor. The implementation of the filters should be done with integer arithmetic and will definitely require an integer arithmetic logic unit (ALU). The program will be stored in EPROMS and 128 bytes of RAM for working memory should suffice. If the acceleration is sampled each 1/4 foot then at 50 mph the maximum time available could be 3.4 msec to complete all computations in the loop. With this in mind, the filters should probably be only second order. Also if it becomes necessary, high speed 16 bit by 16 bit multipliers are available.

A diagram of the probable microprocessor layout is shown in Figure 3. The time constant for the averaging circuit is 1/T and should probably be selected to be about 3 seconds. Hopefully the first order averaging circuit will be adequate.
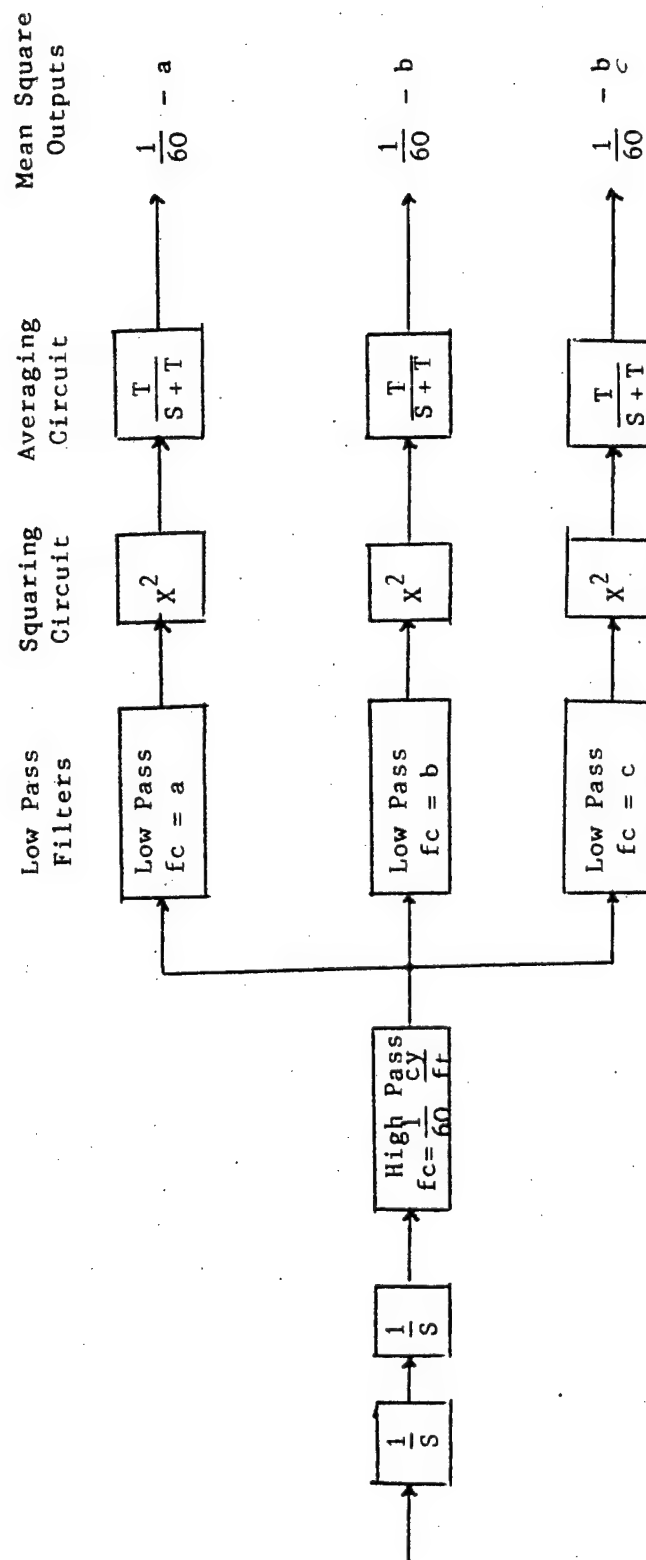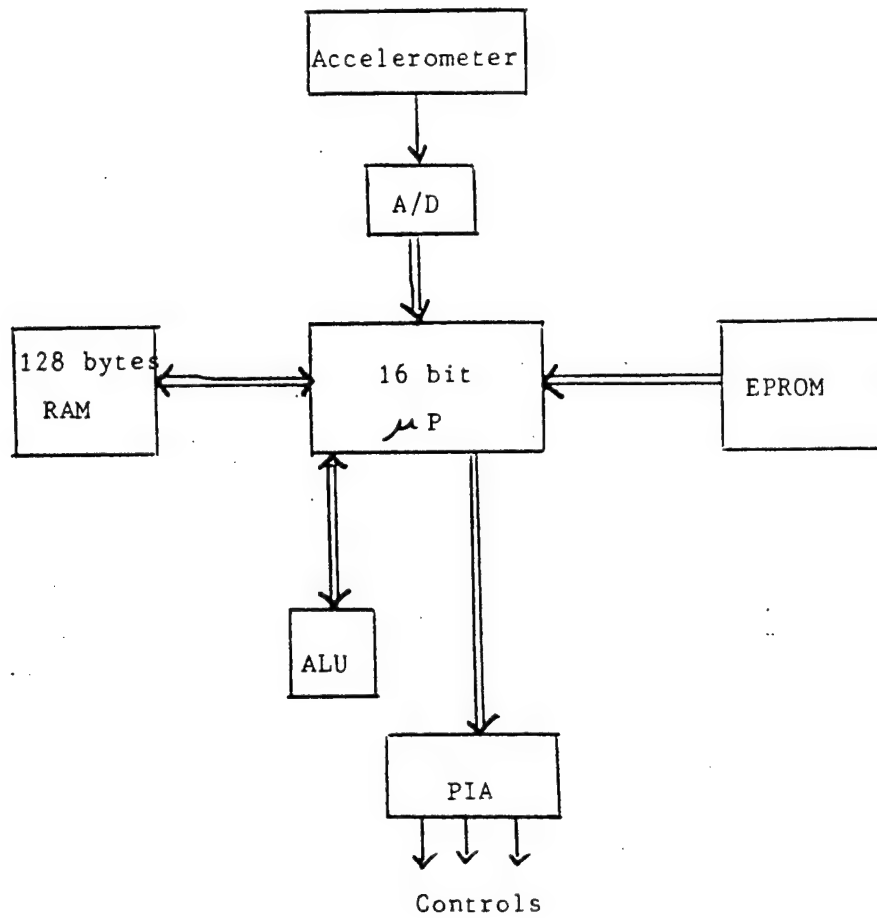
FIGURE 2 Proposed Filtering Scheme

FIGURE 3 Microprocessor Configuration

Sensor Alternatives

Three specific types of sensors were considered for incorporation into the adaptive suspension system. These were (1) a sonar reflective sensor, (2) a pressure transducer, and (3) an accelerometer. Each of these sensors has certain advantages and disadvantages which will be discussed briefly.

Sonar Reflective Sensor

A sensor of this type could be mounted to the underside of the hull, perhaps near the center, and could provide the distance between the hull and the ground. The particular unit looked at (made by Polaroid) was capable of measuring distances of from 0.9 ft. upt to 35 ft. to the nearest 0.1 feet. The sampling frequency was limited to 5 readings per second. This maximum sampling frequency was designed into the sensor in order to obtain a maximum range of 35 feet. The sound requires 62 ms to travel the 35 feet out and back and therefore, limits the design frequency to something less than 16 readings per second, far less than required in this application. If the range were limited to say 3.5 ft maximum, the the maximum transmission time would be reduced to 6.2 ms and perhaps a rate of 100 samples per second could be achieved. The original requirement was to sample at least 73 times per second (every foot at 50 mph). It should be noted that if a radar device were used a 50 nanosecond output pulse would cause a minimum range of 25 ft. and therefore would not be practical for this application.

Another, and perhaps more serious problem exists with the use of any reflective type sensor. The information received would provide only the relative distance between the hull and ground at any point in time. This is not the same as providing the terrain profile height. A detailed analysis was performed to investigate the degree of correlation between this measured signal and the actual profile height. The T95 was simulated over three terrains of various surface roughness (1.15 in, 2.17 in, and 3.88 in rms) and at various vehicle velocities.

The resulting correlation between the ground profile and the relative displacement between the hull and the terrain can be seen in the following Figures 4 thru 15.

Each of the profiles was filtered with a two pole high pass filter with a spatial cutoff frequency of 1/60 cycle/foot. The two signals of interest diverge greatly at times indicating the vertical movement of the hull. Even though this hull movement has a lower frequency content than much of the profile signal, it is still significantly within the band of interest.

In order to successfully utilize a reflective sensor it would also be necessary to include instrumentation to determine the hull vertical position relative to the earth and to remove its effect. This could be done with a hull mounted accelerometer and would permit the estimation of the roadwheel height, and therefore the profile height from the combination of the two sensor outputs.

Pressure Transducer

It was conjecured that a pressure transducer installed within the hydropneumatic suspension system could provide a reading that could readily be converted to spring force. The processor could then make the conversion through a table look up to obtain the spring deflection. This technique would provide a relatively clean signal and the sensor would not be subjected to the environment. Also the samples could be digitized under command of the microprocessor and would not be restricted to the relatively low sample rates of the sonar reflective sensor. Unfortunately it would also only provide relative information of profile height with respect to the hull's vertical position. Therefore, a hull accelerometer would also be required in order to obtain a good estimate of the profile height.

Accelerometer

The third sensor option considered was to use a single accelerometer mounted on the third roadarm as near to the road-wheel as possible. The accelerometer should be mounted in a position such that a true vertical reading is obtained when approximately 2 inches of jounce travel have been encountered. The 2" value is somewhat arbitrary but is selected in an attempt to minimize the geometric errors caused by the roadarm rotation.

This option was selected despite the problems of mounting the accelerometer in an exposed location and despite the added geometric considerations due to roadarm rotation. Since an accelerometer would also be required in other sensor options (though it could be mounted internally), the single accelerometer approach seems more reasonable at least in the test bed phase.

Terrain	Roughness (rms)	Simulation Results	
		MPH	WATTS
APG30	(1.15")	30	0.88
		35	1.33
		40	2.00
		45	3.01
		50	4.40
APG29	(2.17")	20	3.97
		25	5.89
APG31	(3.88")	12	4.55
		15	11.58

Table 1

T95 VRIDE Simulation Results

ADAPTIVE SUSPENSION SYSTEM PROGRAM SUMMARY

OBJECTIVE: To develop a suspension system with the inherent capability to adjust operating characteristics to suit changing terrain inputs. This capability would result in improved vibration isolation with accompanying gains in ride quality and gun platform stability.

GENERAL OPERATION: On-vehicle sensors will measure the terrain profile as it is being traversed. The suspension characteristics needed for optimum performance in this terrain will be determined from a suspension optimization program in the on-borad microprocessor memory. The suspension system will then be automatically adjusted to provide optimum performance.

HARDWARE REQUIREMENTS:

    a. Terrain Sensors

    b. On-Vehicle Microprocessor

    c. Servo Controls for Suspension

    d. Variable Suspension System

SOFTWARE REQUIREMENTS:

    a. Microprocessor Logic Package

        (1) Process Terrain Data

        (2) Identify the terrain range in which the vehicle is operating.

        (3) Determine suspension requirements for existing terrain range; (from pre-established program in microprocessor memory).

        (4) Send Servo control signals to make necessary suspension adjustments.

    b. Suspension Optimization Hybrid Computer Program

FUNCTIONAL OPERATION: Sensors will measure the terrain profile as it is being traversed and provide input to the on-board micro-

processor. The microprocessor will process the terrain sensor data to provide a measure of the terrain profile such as the PSD and/or RMS. This measured terrain profile data will then be compared with a set of representative terrain ranges from the hybrid suspension optimization program in the microprocessor memory and the terrain range in which the vehicle is operating will be identified. The corresponding optimimum suspension parameters for this terrain will also be simulataneously identified. The microprocessor will then send the required Servo control signal to make the necessary suspension adjustments.

GENERAL REQUIREMENTS:

a. System must be capable of functioning at vehicle speeds of up to 50 MPH.

b. System must be capable of functioning on terrain profiles up to 4 RMS.

c. Initial terrain profiles must be developed in not more than five seconds and updated every second.

d. Terrain profile to be measured in one foot increments.

e. System will incorporate a manual overdrive.

PROGRAM DEVELOPMENT ELEMENTS:

a. Hybrid computer suspension optimization program development.

b. Terrain sensor/microprocessor/microprocessor logic package development.

c. T95 vehicle modification and evaluation.

T95 41 TON TANK
30 MPH ON   APG30   (1.15 IN. RMS)   10 NOV 76

SIGNAL IDENTIFICATION   WHEEL   3 TO CHASSIS   DISPLACEMENT

```
NO. OF SAMPLES        762
SAMPLE RATE           128.    SAMP/SEC
MINIMUM VALUE         -.466   FEET
MAXIMUM VALUE          .183   FEET
AVERAGE VALUE         -.092   FEET
RMS OF SIGNAL          .130   FEET
```

SIGNAL B IDENTIFICATION   HP .7 HZ WHEEL NUMBER   3   PROFI
LE ELEVATION

```
MINIMUM VALUE         -.232   FEET
MAXIMUM VALUE          .195   FEET
AVERAGE VALUE         -.003   FEET
RMS OF SIGNAL          .077   FEET
```

OPTIONS AVAILABLE : STOP=-1, DEFINE SIGNAL=0; FILTER SIGNAL=1 ; PSD=2;
PLOT SIGNAL=3; HISTOGRAM=4; CROSS PLOT=5; DUAL PLOT=6; CROSS CORRELATI
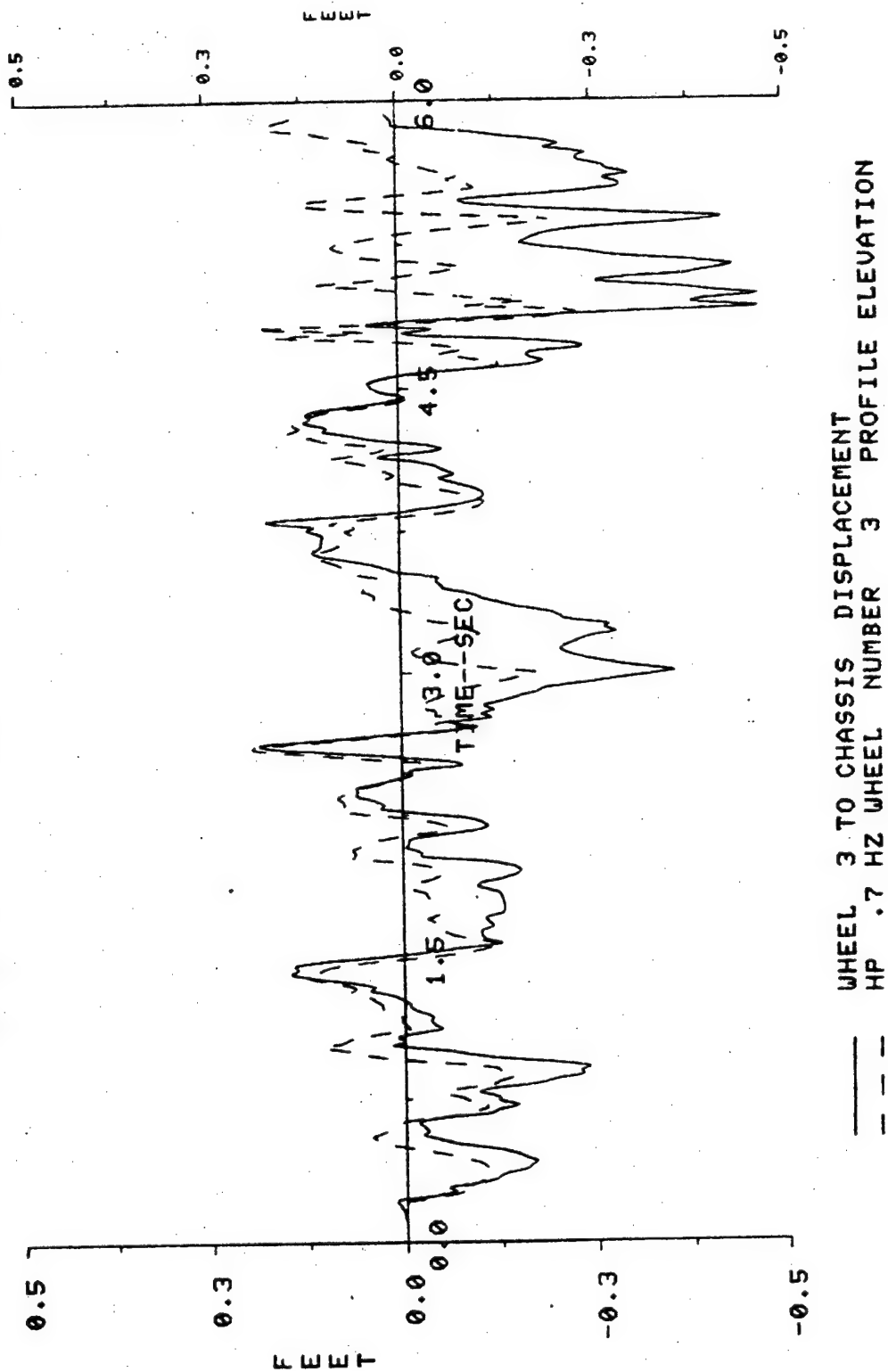ON=7 :

A-12

FIGURE 4

FIGURE 5

T95 41 TON TANK
WHEEL 3 TO CHASSIS DISPLACEMENT
HP .7 HZ WHEEL NUMBER 3 PROFILE ELEVATION

FIGURE 6

T95 41 TON TANK
45 MPH ON   APG30   (1.15 IN. RMS)   10 NOV 76

SIGNAL IDENTIFICATION   WHEEL 3 TO CHASSIS DISPLACEMENT

```
NO. OF SAMPLES       1017
SAMPLE RATE          256.       SAMP/SEC
MINIMUM VALUE        -.565      FEET
MAXIMUM VALUE         .188      FEET
AVERAGE VALUE        -.146      FEET
RMS OF SIGNAL         .167      FEET
```

SIGNAL B IDENTIFICATION   HP 1.1 HZ WHEEL NUMBER 3   PROFI
LE ELEVATION

```
MINIMUM VALUE        -.231      FEET
MAXIMUM VALUE         .201      FEET
AVERAGE VALUE        -.003      FEET
RMS OF SIGNAL         .076      FEET
```

OPTIONS AVAILABLE + STOP=-1; DEFINE SIGNAL=0; FILTER SIGNAL=1 ; PSD=2;
PLOT SIGNAL=3; HISTOGRAM=4; CROSS PLOT=5; DUAL PLOT=6; CROSS CORRELATI
ON=7 ?

FIGURE 7

A-15

T95 41 TON TANK
45 MPH ON   APG30 -(1.15 IN. RMS)   10 NOV 76

——— WHEEL 3 TO CHASSIS DISPLACEMENT
— — — HP 1.1 HZ WHEEL NUMBER 3 PROFILE ELEVATION

FIGURE 8

A-16

T95 41 TON TANK
WHEEL 3 TO CHASSIS DISPLACEMENT
HP 1.1 HZ WHEEL NUMBER 3 PROFILE ELEVATION
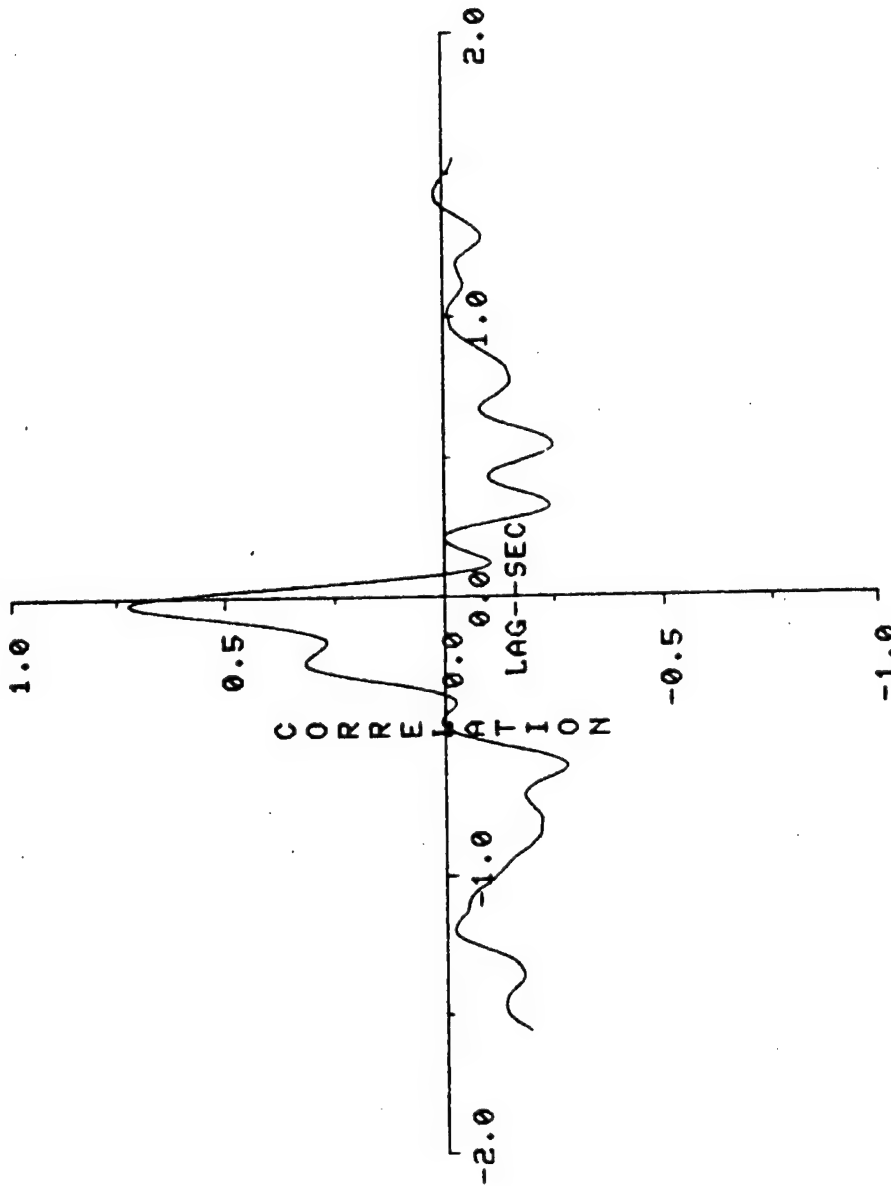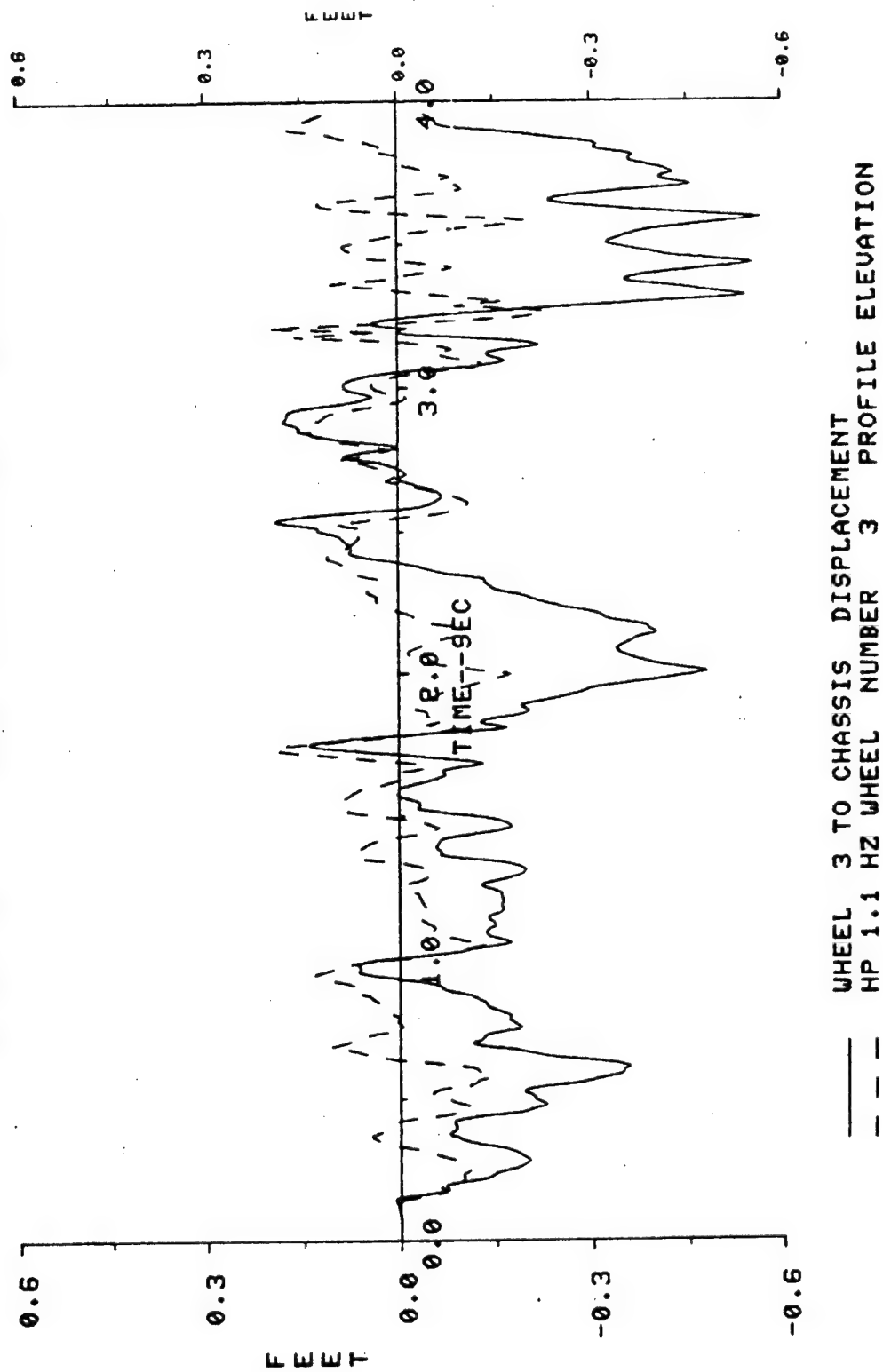
FIGURE 9

A-17
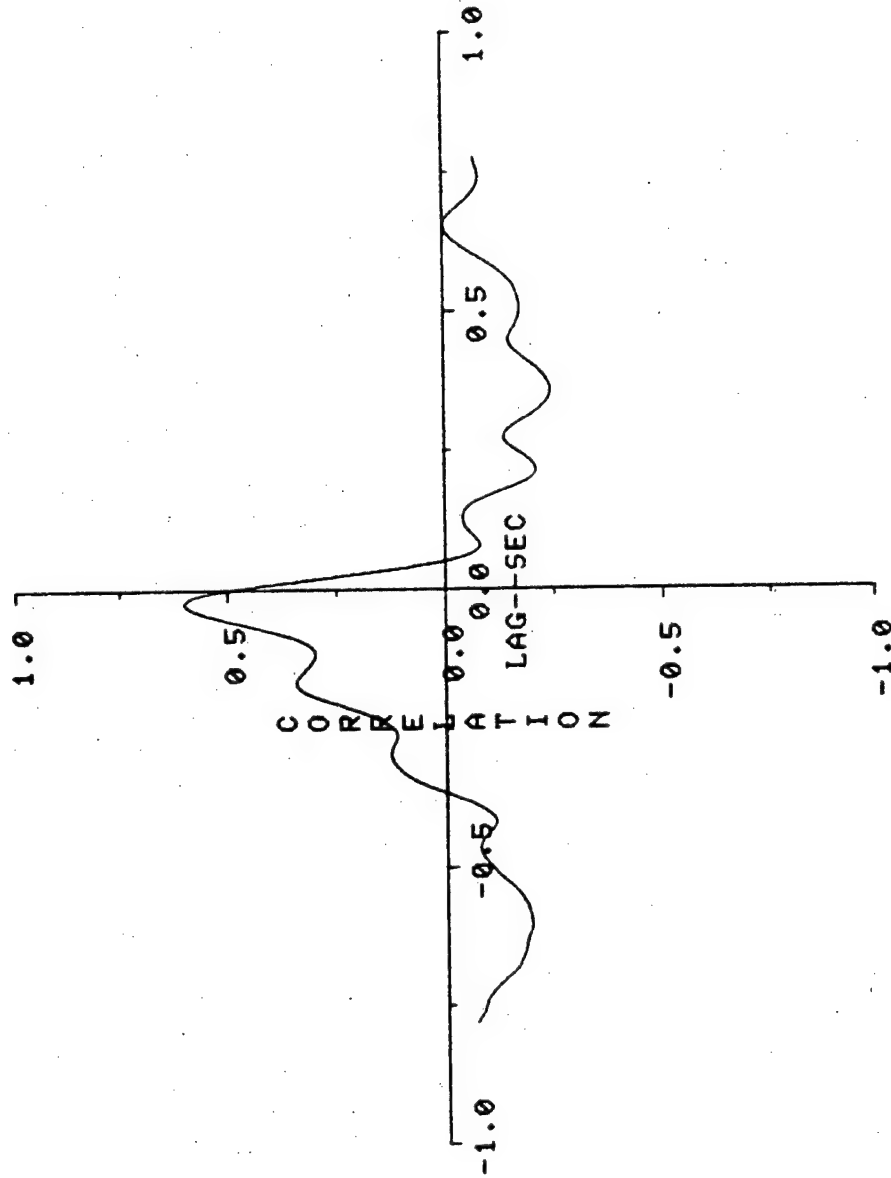
T95 41 TON TANK
25 MPH ON   APG29   (2.17 IN. RMS)   11 NOV 76

SIGNAL IDENTIFICATION   WHEEL 3 TO CHASSIS DISPLACEMENT

                NO. OF SAMPLES   544
                SAMPLE RATE   64.   SAMP/SEC
                MINIMUM VALUE   -.657   FEET
                MAXIMUM VALUE   .410   FEET
                AVERAGE VALUE   -.130   FEET
                RMS OF SIGNAL   .220   FEET

        SIGNAL B IDENTIFICATION   HP .6 HZ WHEEL NUMBER   3   PROFI
LE ELEVATION

                MINIMUM VALUE   -.641   FEET
                MAXIMUM VALUE   .475   FEET
                AVERAGE VALUE   -.008   FEET
                RMS OF SIGNAL   .207   FEET

OPTIONS AVAILABLE : STOP=-1; DEFINE SIGNAL=0; FILTER SIGNAL=1 ; PSD=2;
PLOT SIGNAL=3; HISTOGRAM=4; CROSS PLOT=5; DUAL PLOT=6; CROSS CORRELATI
ON=7 :

FIGURE 10

A-18

T95 41 TON TANK
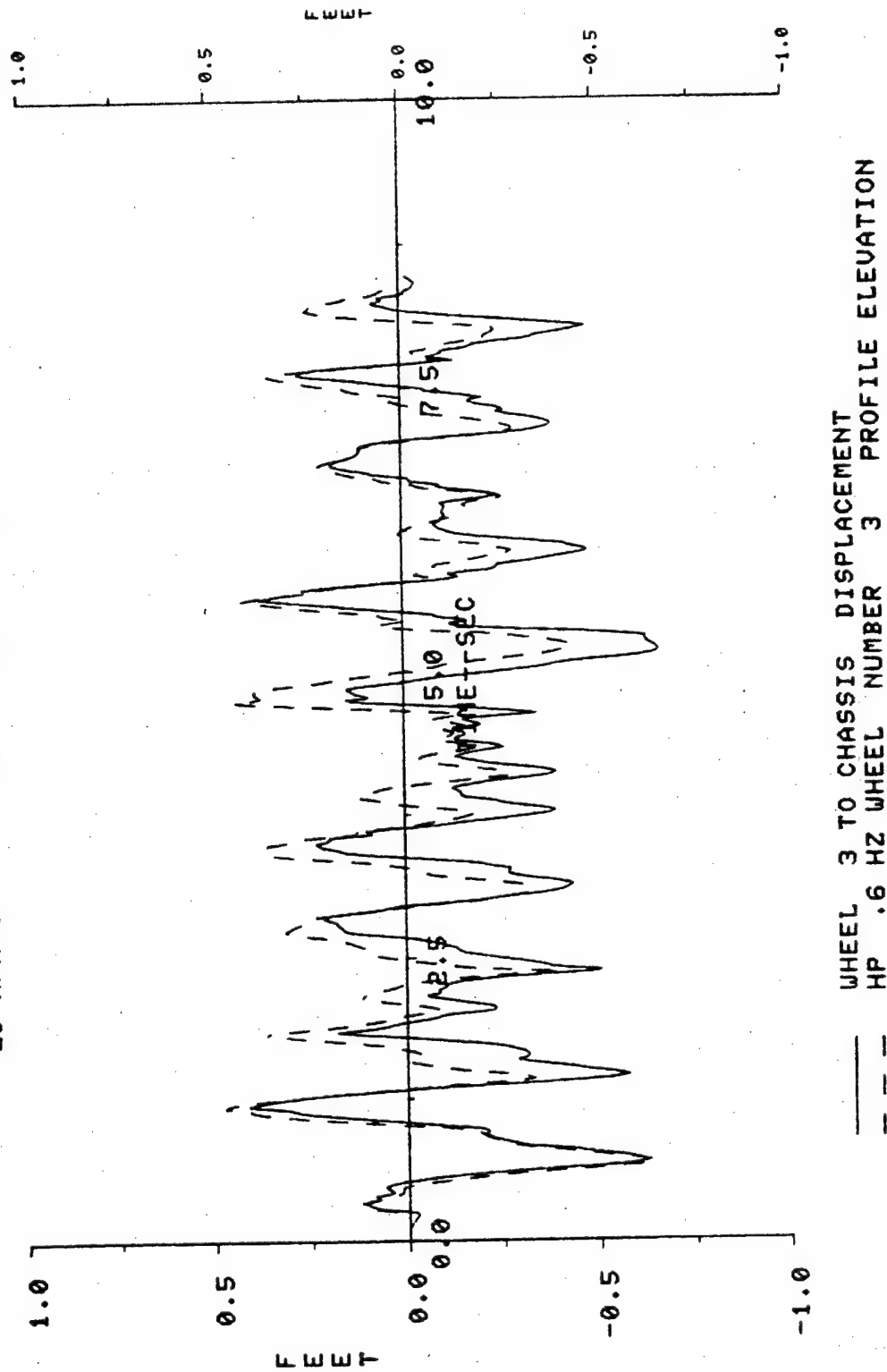25 MPH ON   APG29   (2.17 IN. RMS)   11 NOV 76

FIGURE 11

WHEEL 3 TO CHASSIS DISPLACEMENT
HP .6 HZ WHEEL NUMBER 3   PROFILE ELEVATION

A-19

T95 41 TON TANK
WHEEL 3 TO CHASSIS DISPLACEMENT
HP .6 HZ WHEEL NUMBER 3 PROFILE ELEVATION

FIGURE 12

A-20
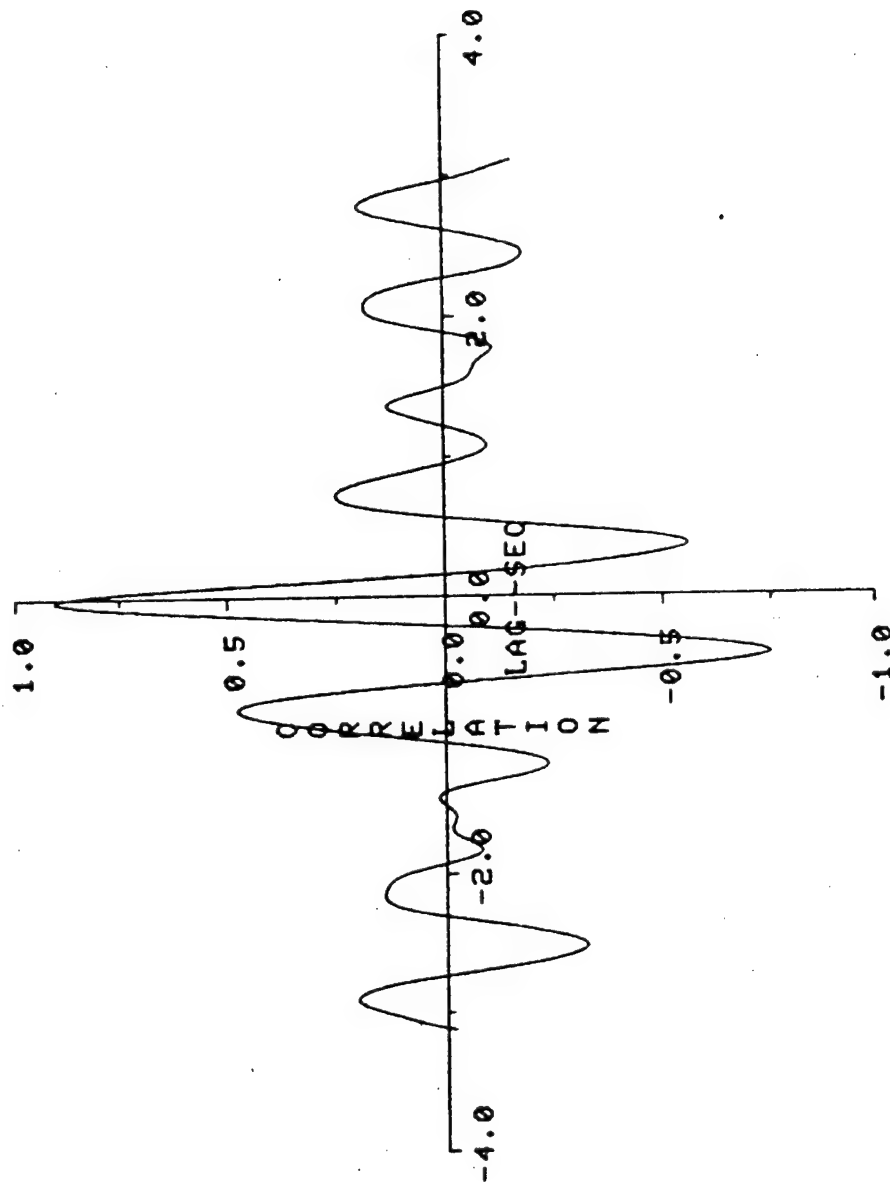
T95 41 TON TANK
12 MPH ON   APG31   (3.88 IN. RMS)   16 NOV 76

SIGNAL IDENTIFICATION   WHEEL   3 TO CHASSIS DISPLACEMENT

NO. OF SAMPLES   1499
SAMPLE RATE   64.   SAMP/SEC
MINIMUM VALUE   -.601   FEET
MAXIMUM VALUE   .262   FEET
AVERAGE VALUE   -.079   FEET
RMS OF SIGNAL   .146   FEET

SIGNAL B IDENTIFICATION   HP .3 HZ WHEEL NUMBER   3   PROFI
LE ELEVATION

MINIMUM VALUE   -.624   FEET
MAXIMUM VALUE   .969   FEET
AVERAGE VALUE   -.002   FEET
RMS OF SIGNAL   .350   FEET

OPTIONS AVAILABLE : STOP=-1; DEFINE SIGNAL=0; FILTER SIGNAL=1 ; PSD=2;
PLOT SIGNAL=3; HISTOGRAM=4; CROSS PLOT=5; DUAL PLOT=6; CROSS CORRELATI
ON=7 :

FIGURE 13

A-21

FIGURE 14

T95 41 TON TANK
WHEEL 3 TO CHASSIS DISPLACEMENT
HP .3 HZ WHEEL NUMBER 3 PROFILE ELEVATION

FIGURE 15

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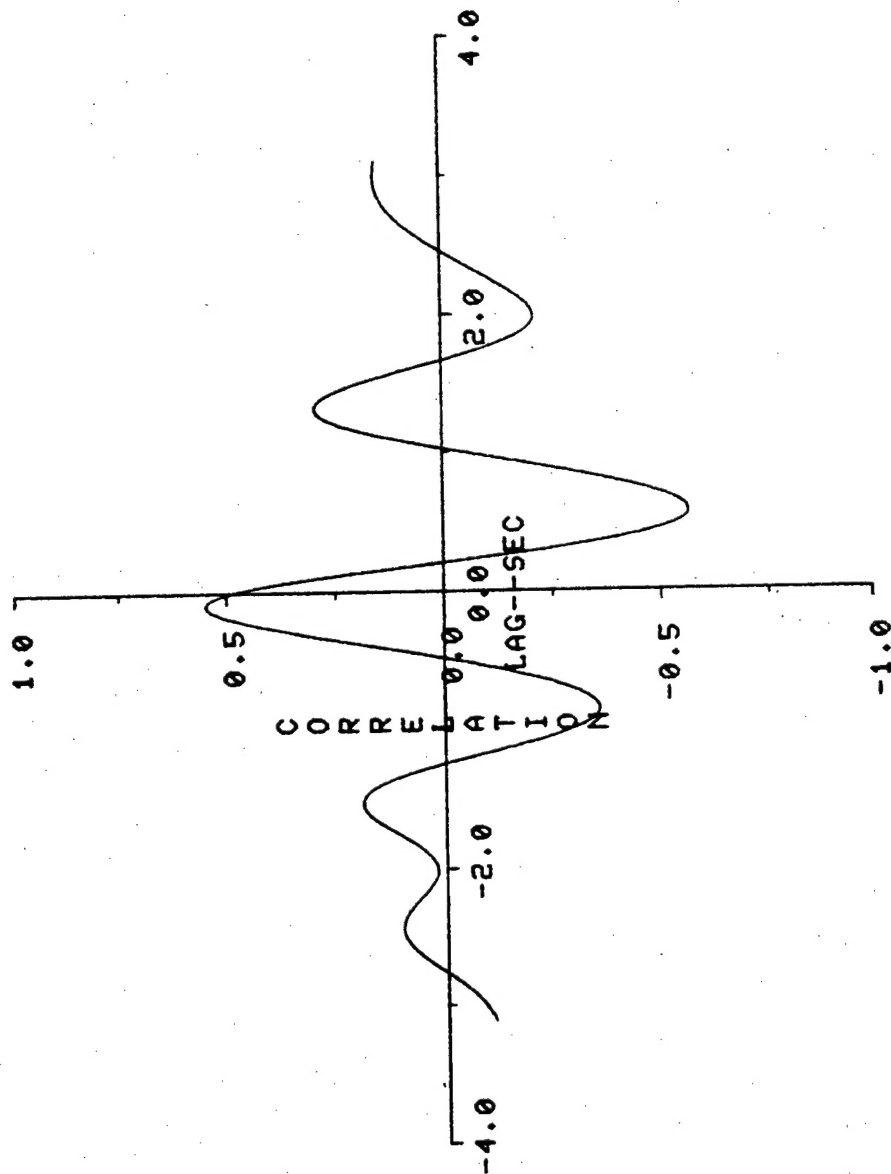
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